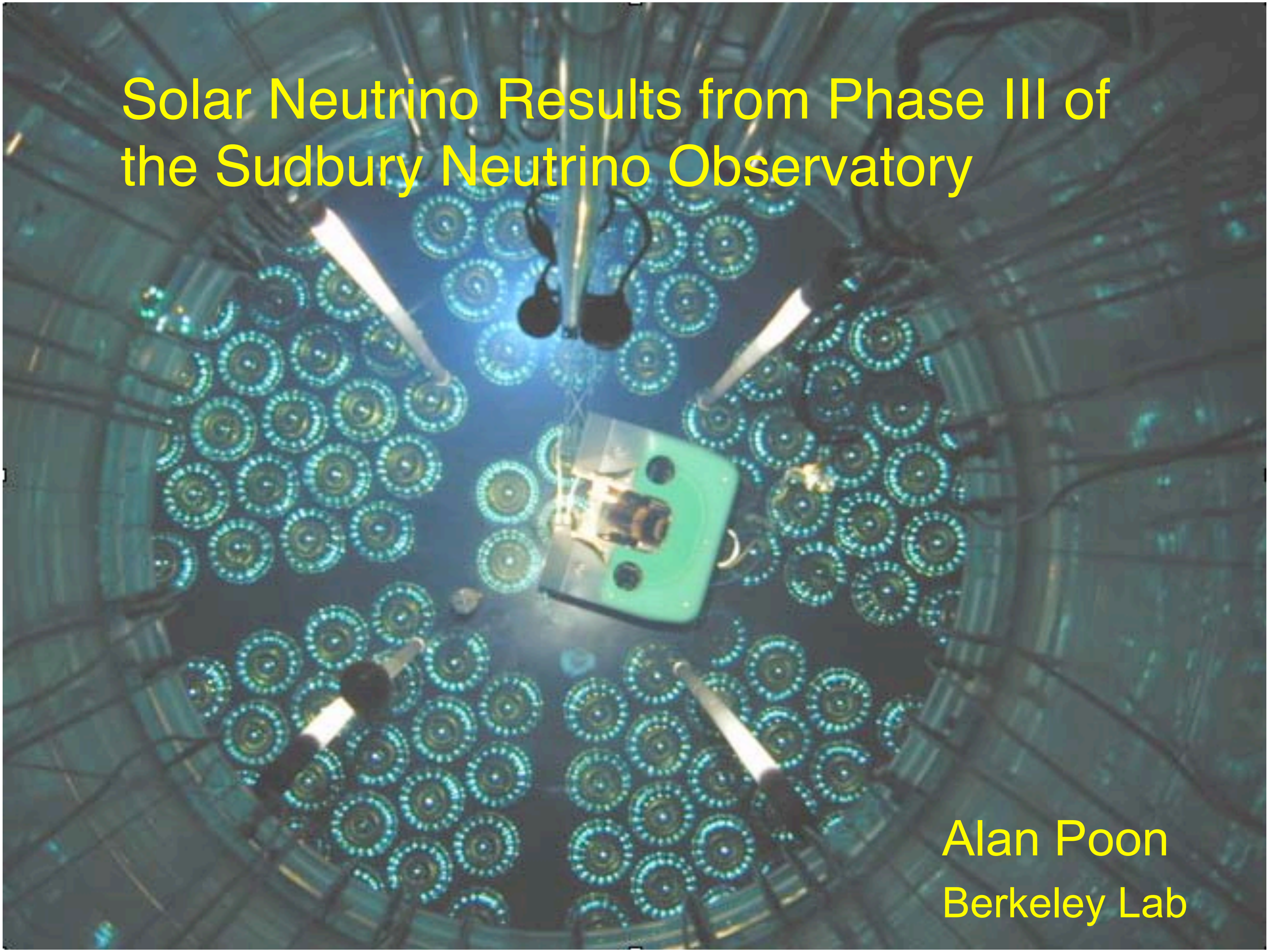
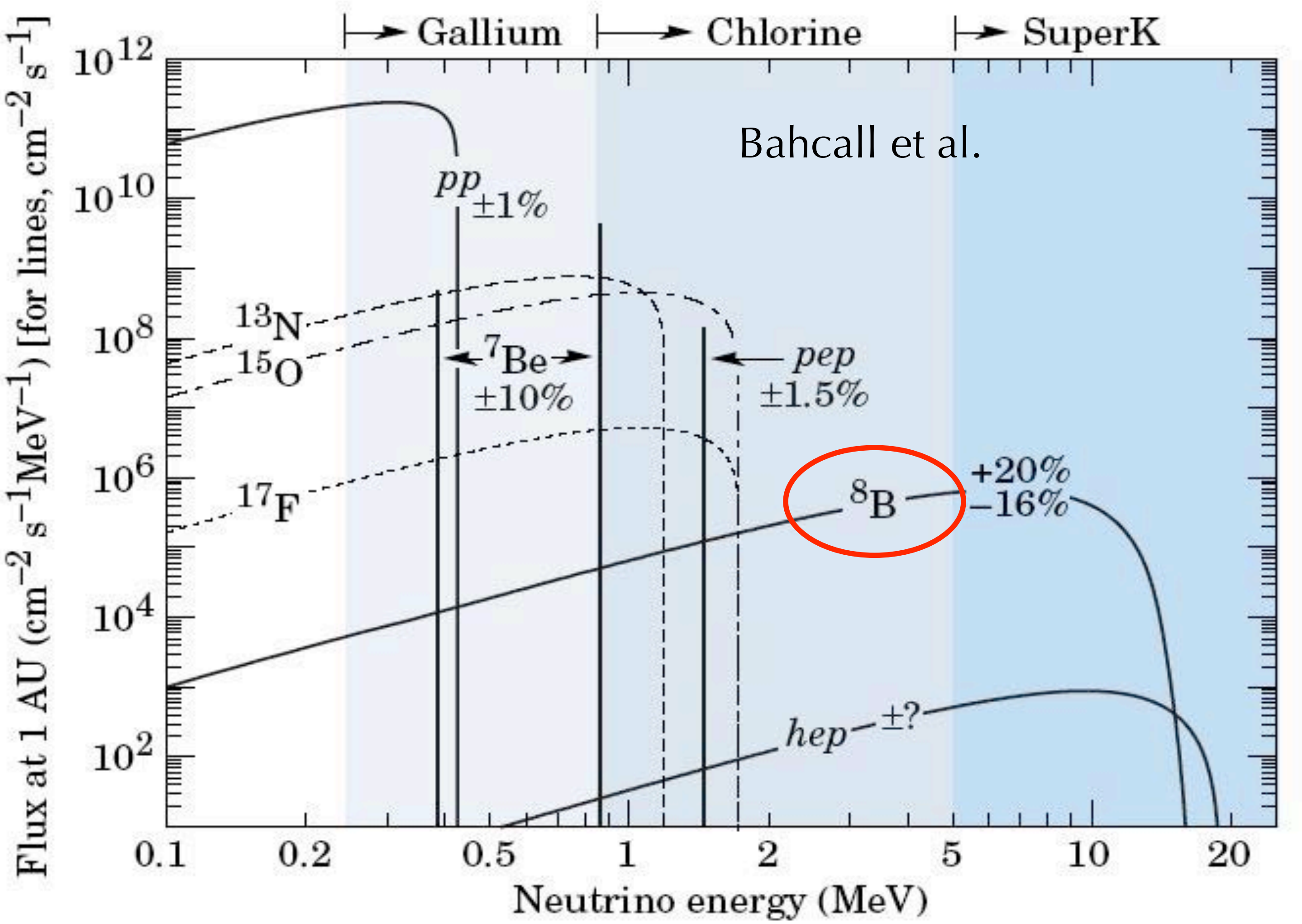
Solar Neutrino Results from Phase III of the Sudbury Neutrino Observatory



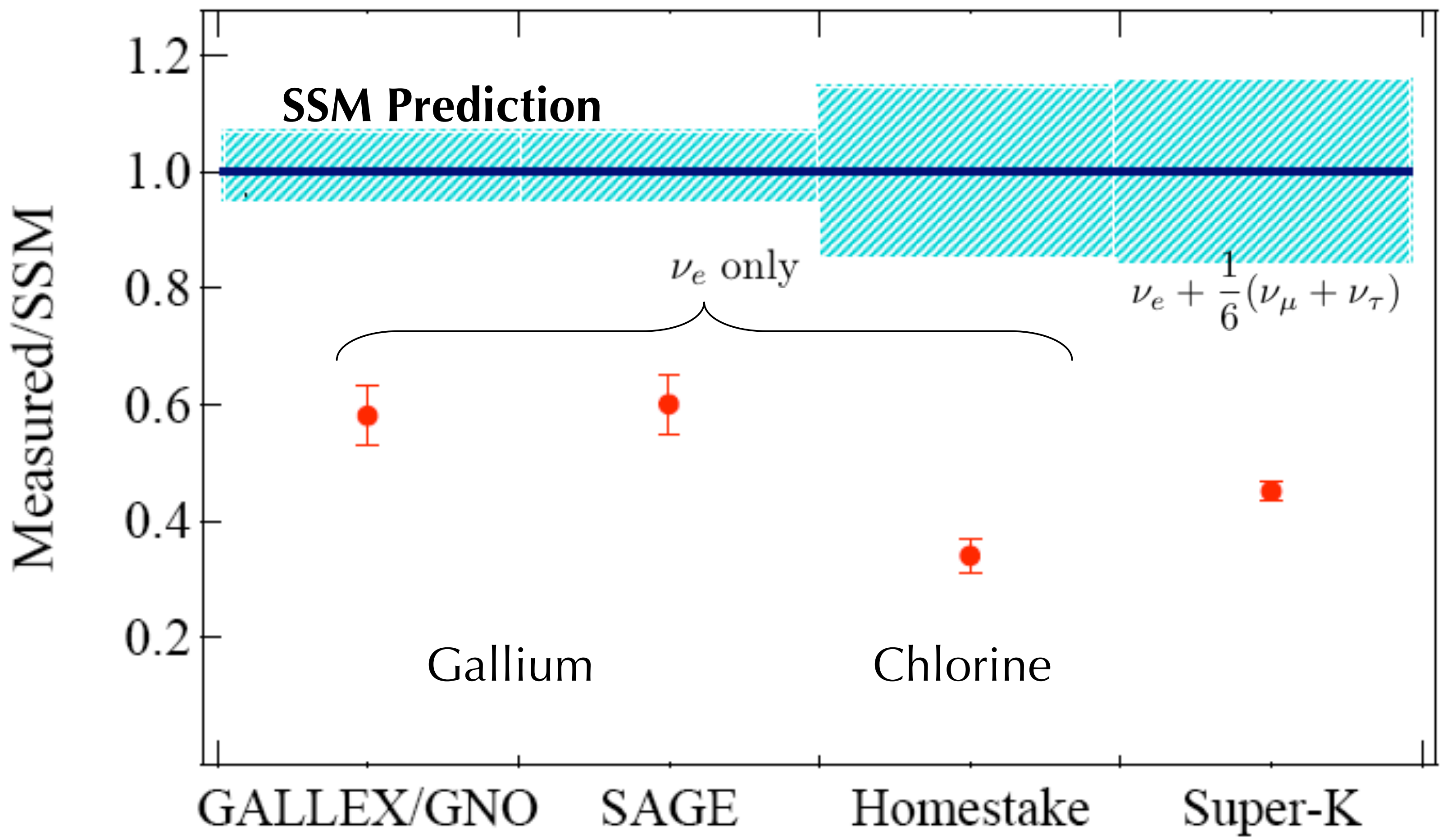
Alan Poon
Berkeley Lab

Solar Neutrinos



Solar Neutrino Problem (~Y2K)

- Deficits were seen in all terrestrial solar ν detectors (which were sensitive primarily to ν_e).



Sudbury Neutrino Observatory (SNO)

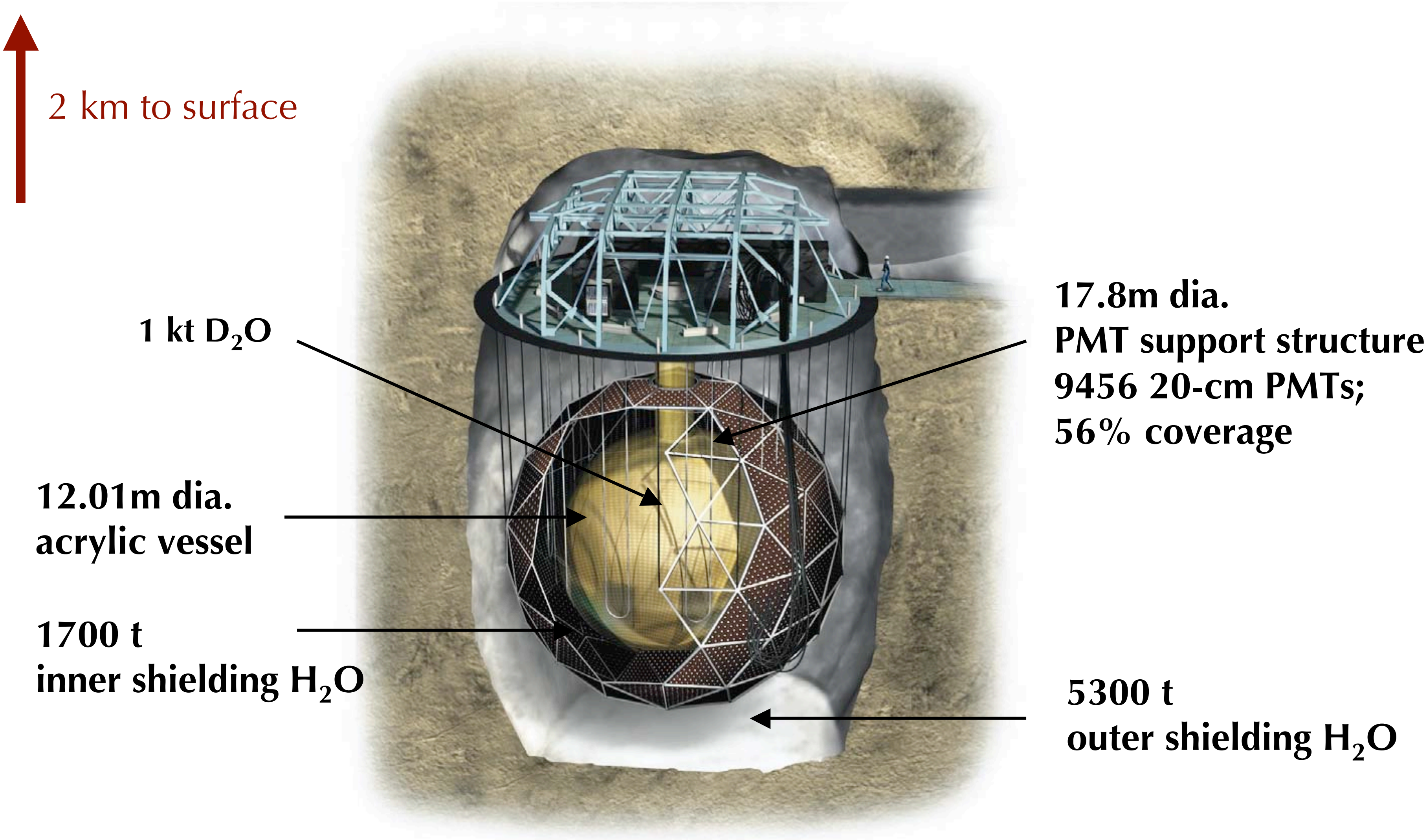


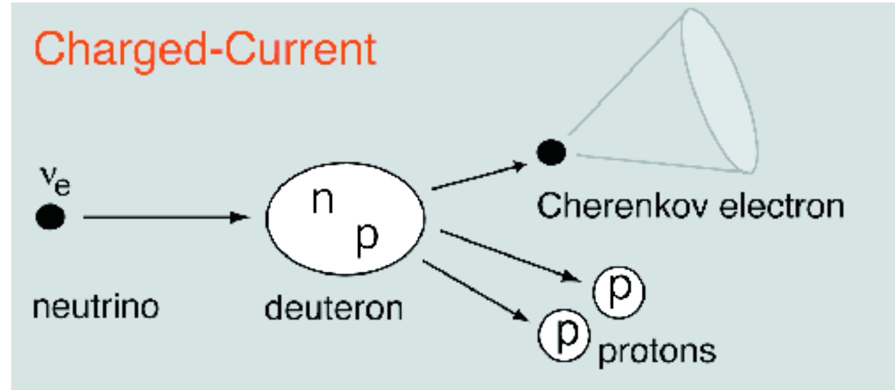
Image courtesy National Geographic

Nucl. Inst. Meth. A449, 127 (2000)

Detecting ν at SNO

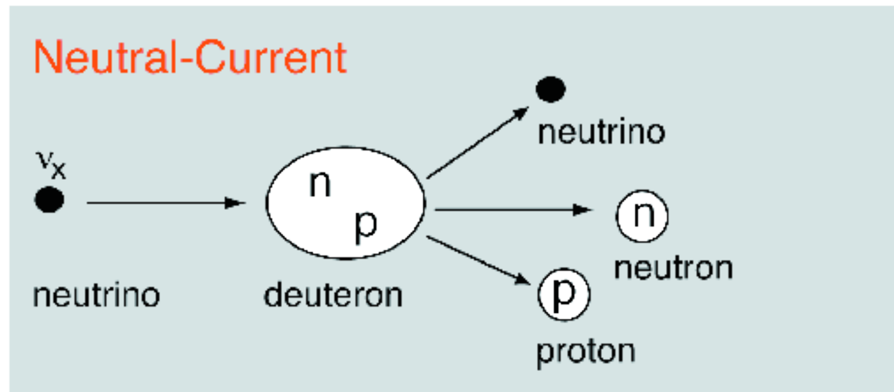
CC $\nu_e + d \rightarrow p + p + e^-$

- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340\cos\theta$



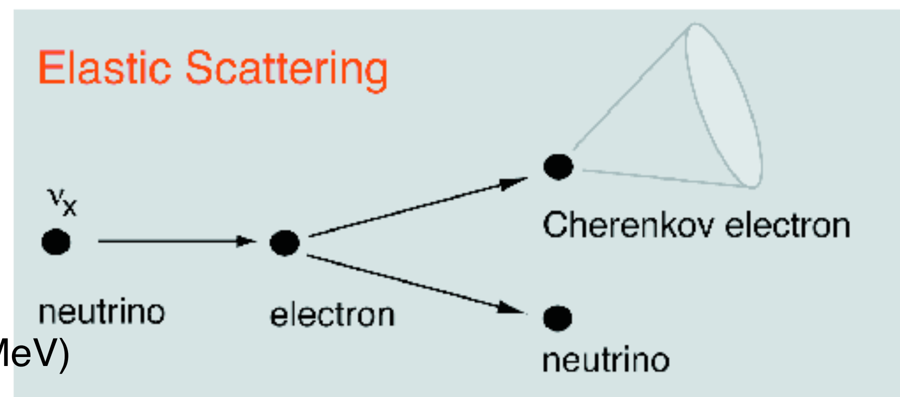
NC $\nu_x + d \rightarrow p + n + \nu_x$

- Measure total ^8B ν flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low Statistics
- $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
- Strong directionality: $\theta_e \leq 18^\circ$ (T_e = 10 MeV)



"Smoking gun" for flavor transformation

Does the total flux of solar neutrinos equal the pure ν_e flux?

Measure:

Transformation to another active flavor if:

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} \Rightarrow \phi^{CC}(\nu_e) < \phi^{NC}(\nu_x)$$

Alternatively…

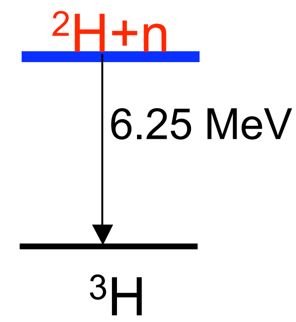
$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)} \Rightarrow \phi^{CC}(\nu_e) < \phi^{ES}(\nu_x)$$

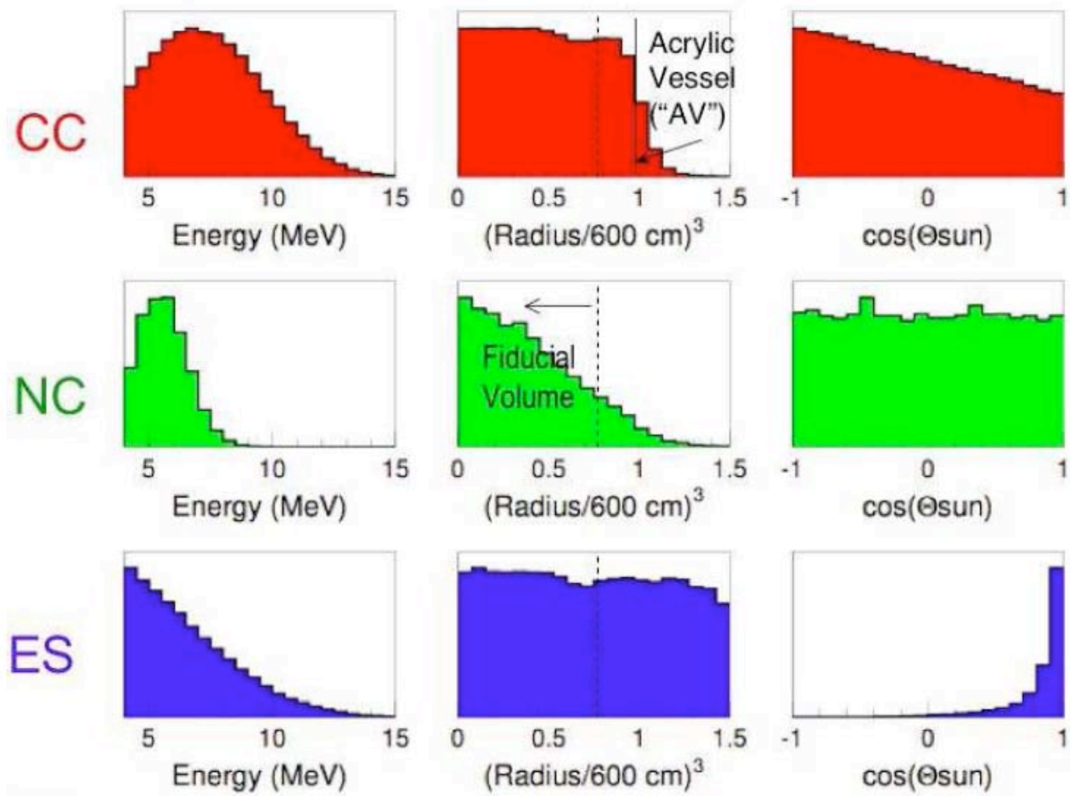
Flavor transformation can be demonstrated without any assumption on the Standard Solar Model prediction of the total neutrino flux.

SNO Phase I: Pure Heavy Water

- **Pure D_2O target** - Ended May 2001
  - n + $^2H \rightarrow {}^3H + \gamma$(6.25 MeV)
  - Low neutron detection efficiency (~14%)

σ = 0.5 mb





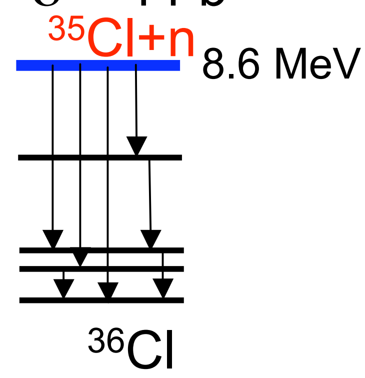
- assumed an undistorted ^8B spectrum; but neutrino oscillation can have energy dependence
- a null hypothesis test
- large NC uncertainties when the energy constraint is removed

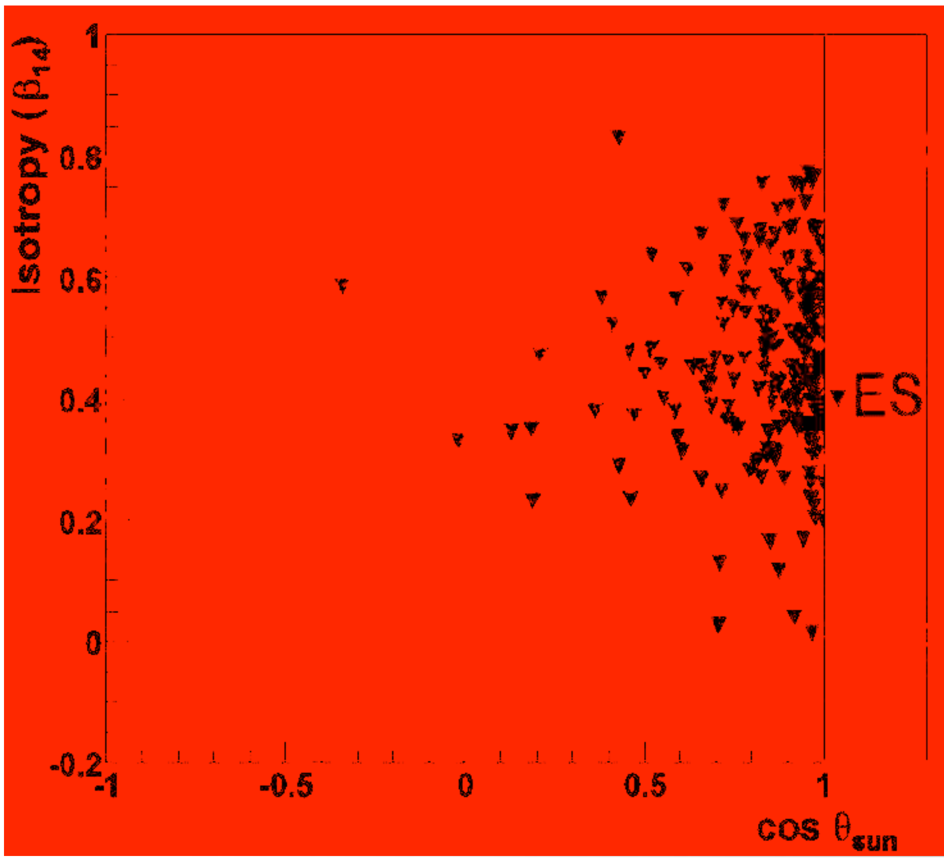
SNO Phase II: Salt

Phase II (D_2O + 2 tonnes NaCl) - Ended Sep. 2003

- n + ^{35}Cl → ^{36}Cl + γ's(ΣE_γ=8.6 MeV)
- High neutron detection efficiency (~41%)

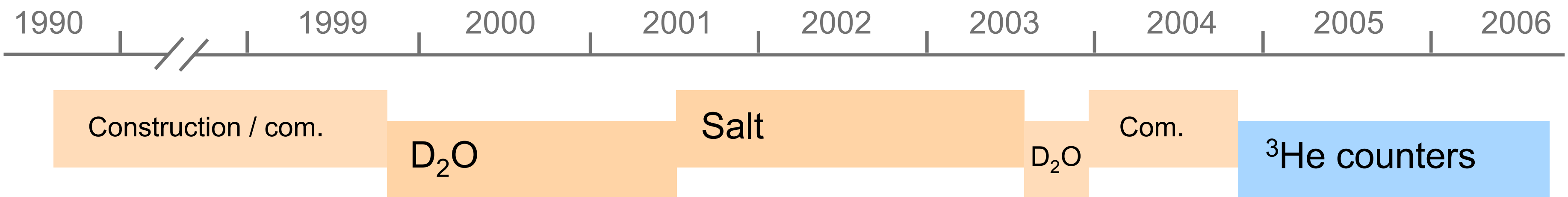
σ = 44 b





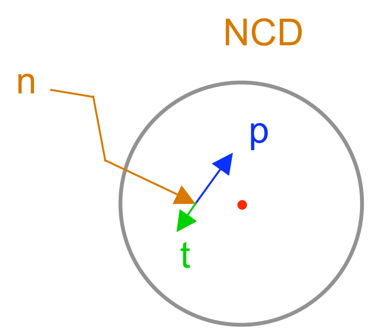
- use of light isotropy removed assumption of ^{8}B shape in physics extraction
- total NC flux uncertainty ~8.4%
- Strong CC-NC anti-correlation (-0.52)

Phase III : ^{3}He counters

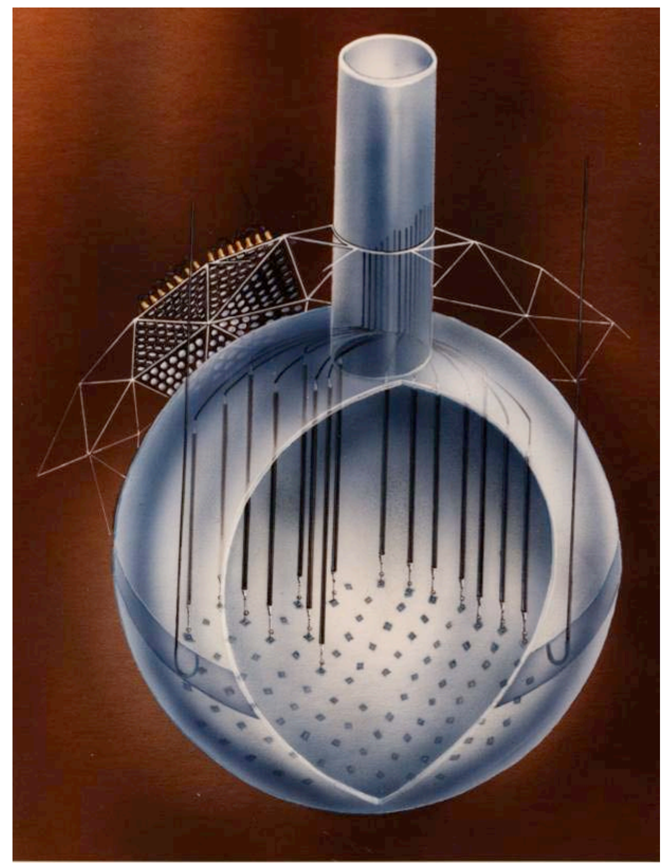


$$n + {}^3He \rightarrow t + p + 764\ keV$$

$$\sigma = 5330\ b \quad \varepsilon_n = 21\ \%$$



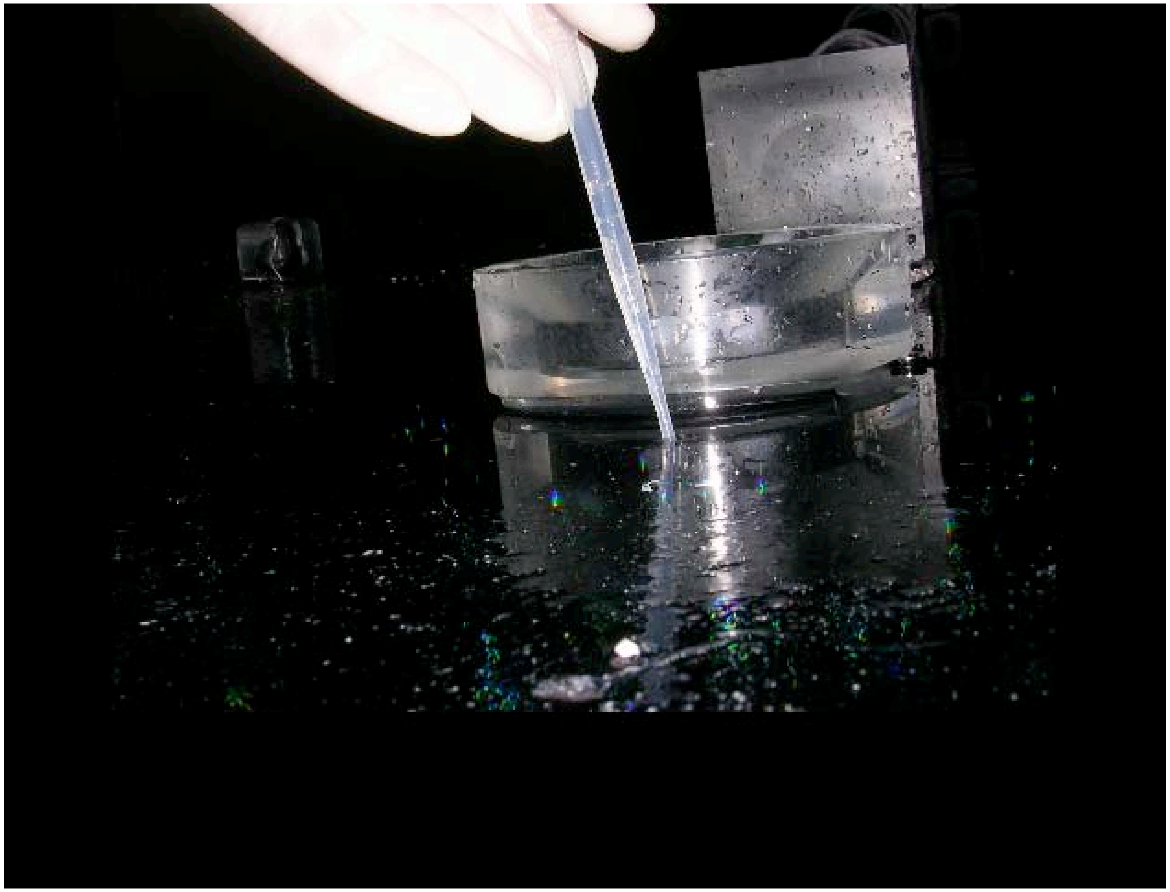
- Different systematics
- Reduce CC-NC correlation
- Better CC flux measurement



SNO Detector: Current Status

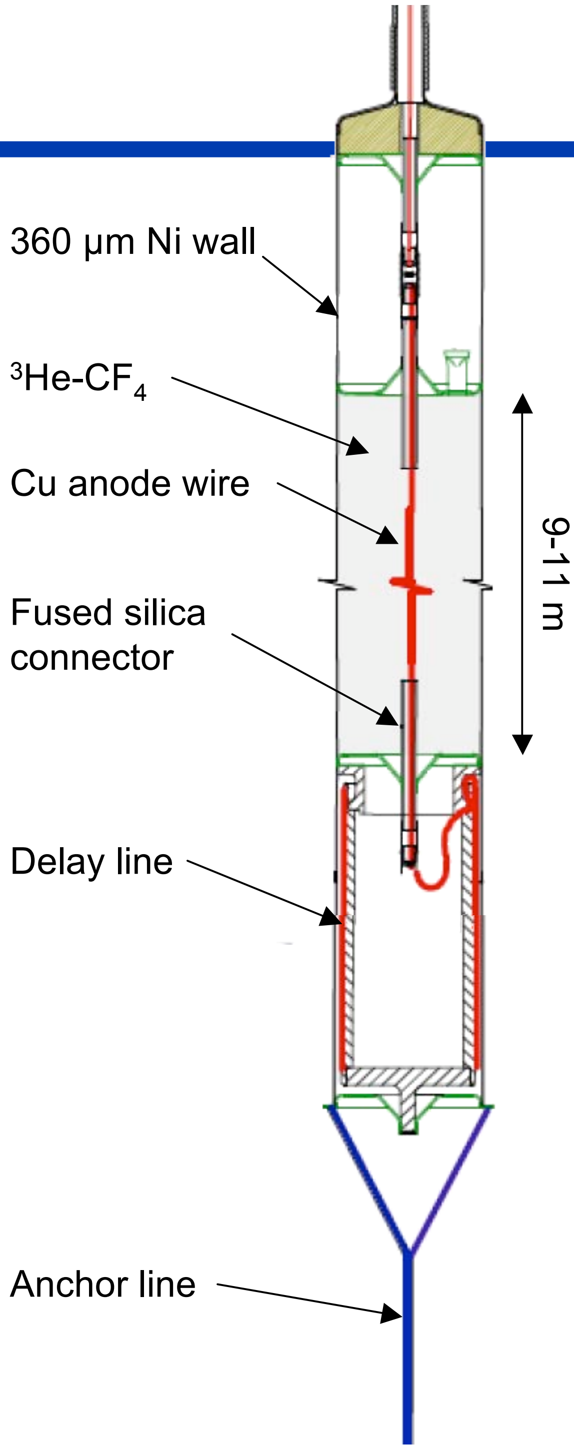
since 28th November, 2006

Getting the Last Drop of D_2O



The acrylic vessel was completely emptied at 14:45 (Sudbury time) on 28th May, 2007.

NCD String

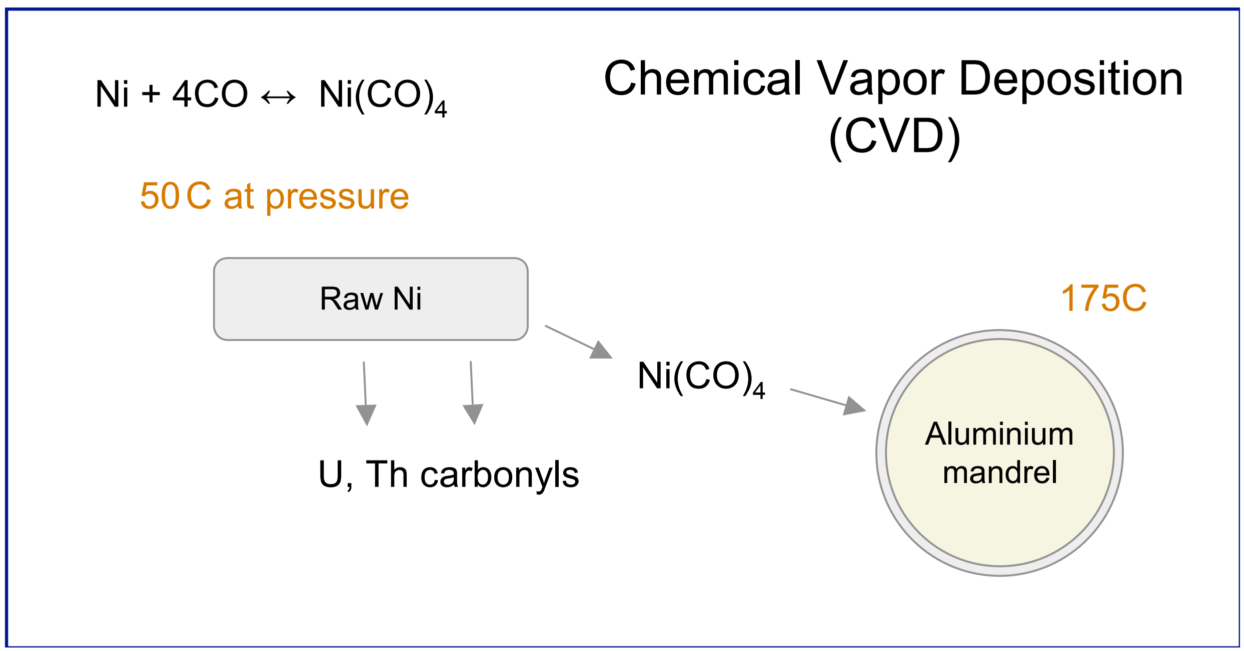


- High purity CVD nickel

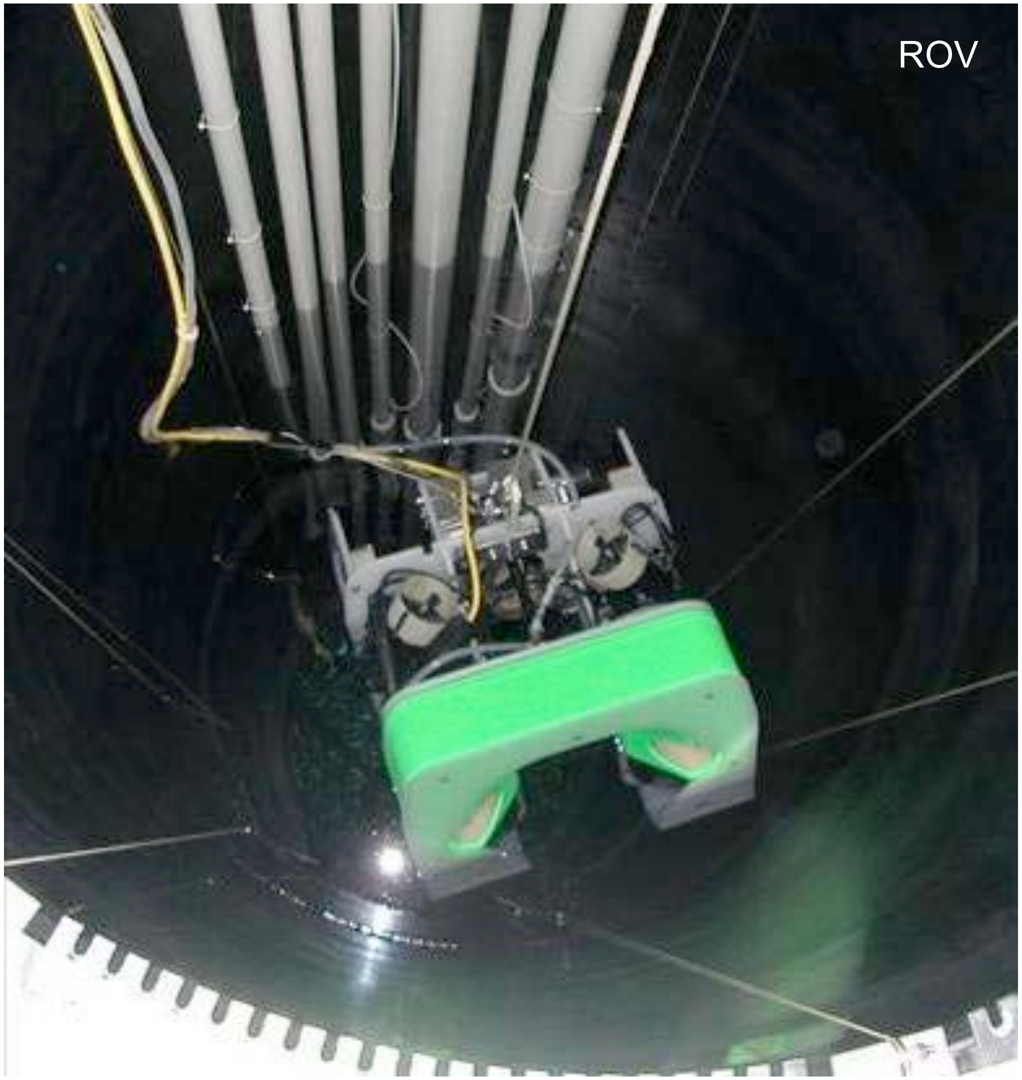
$$gTh/gNCD = 3.43^{+1.49}_{-2.11} \times 10^{-12}$$
$$gU/gNCD = 1.81^{+0.80}_{-1.12} \times 10^{-12}$$

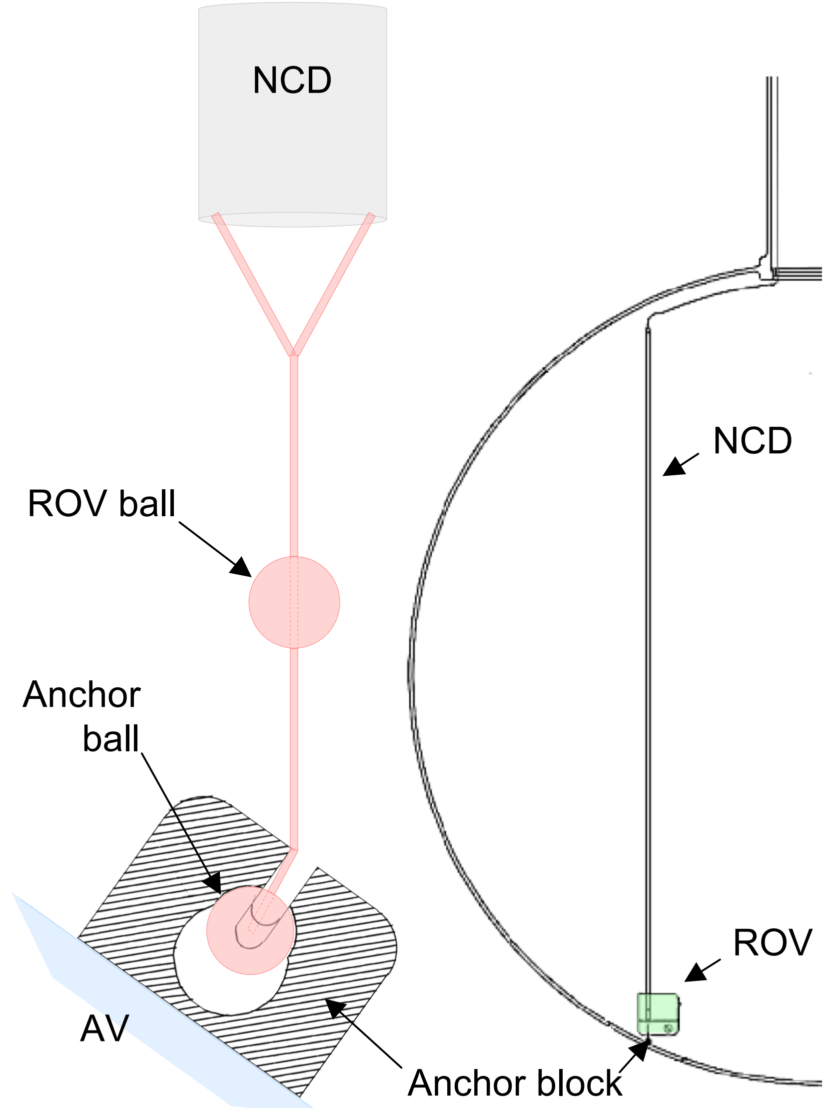
- ~1/100 × background of previously cleanest PC

End cap

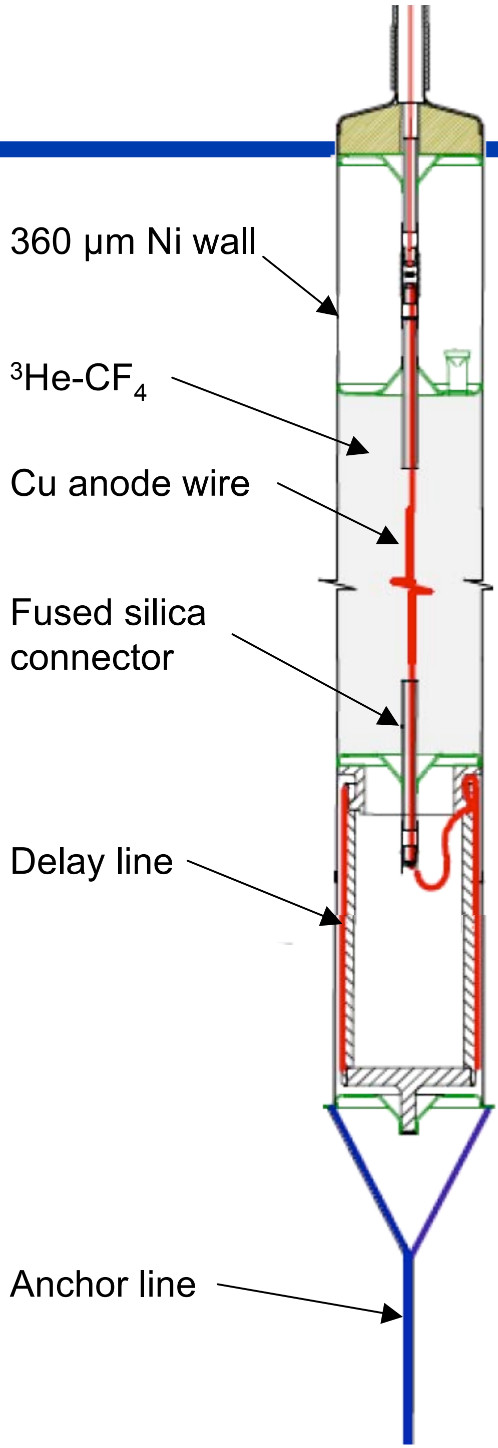


NCD Deployment

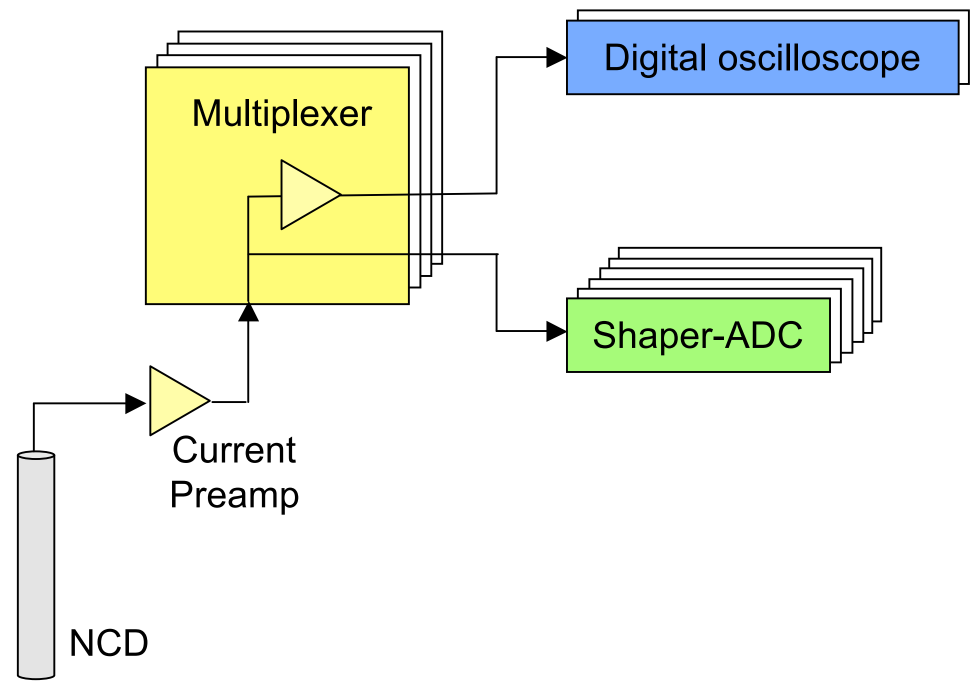




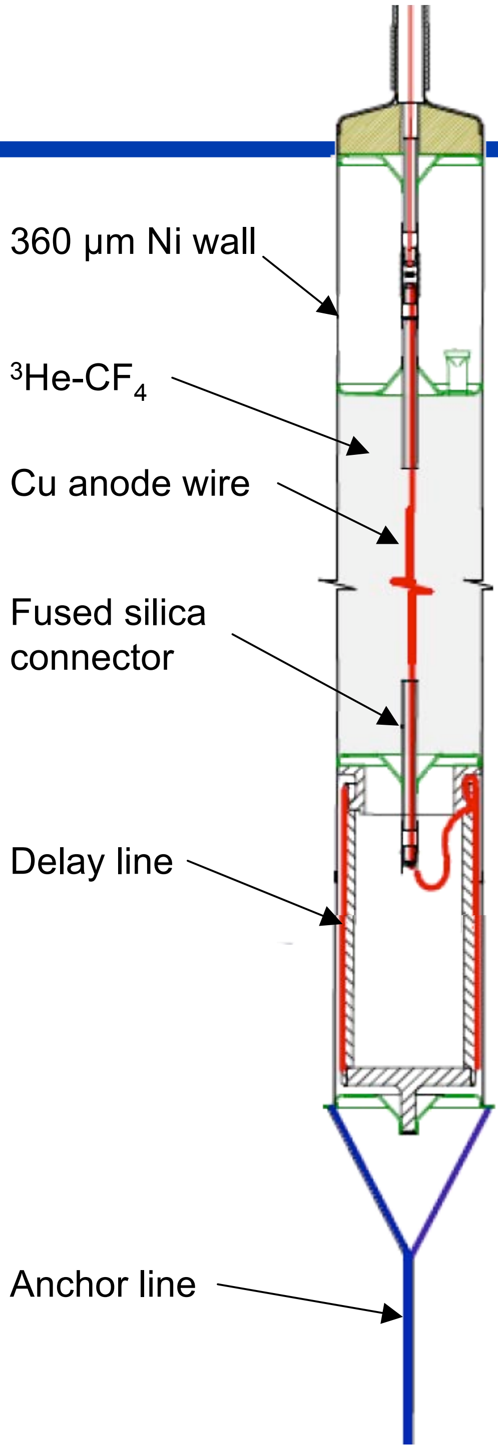
NCD String



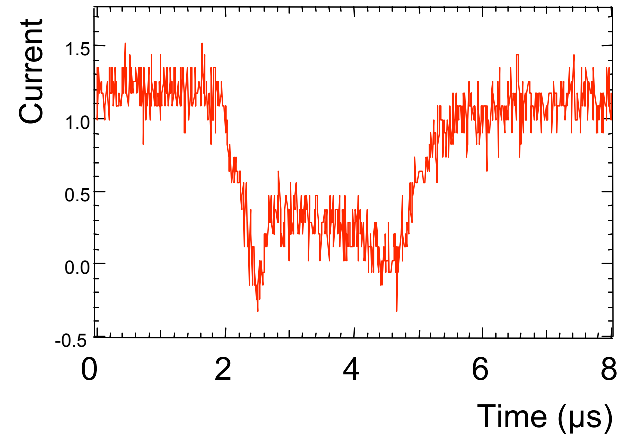
Digital scopes	→	trigger on amplitude slow readout (^{8}B neutrino)
Shaper-ADCs	→	trigger on integral charge fast readout (^{8}B, SN)



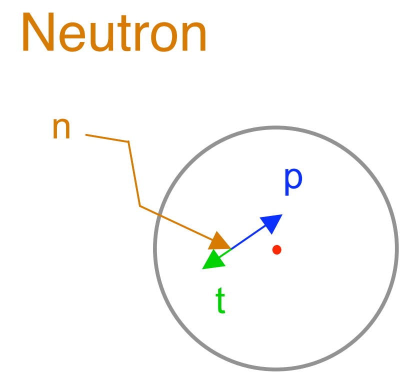
NCD Signals



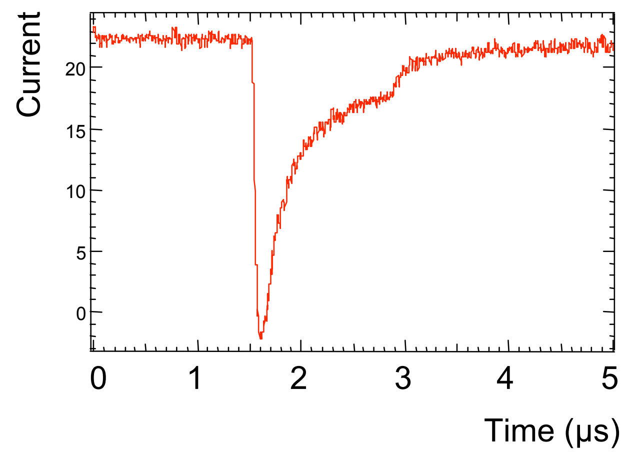
360 µm Ni wall
^{3}He-CF_4
Cu anode wire
Fused silica connector
Delay line
Anchor line



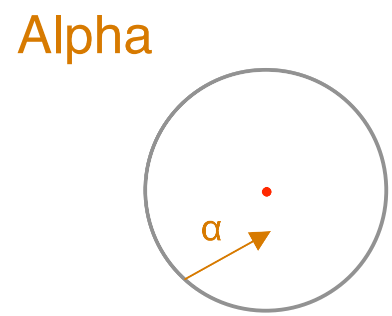
Current
1.5
1.0
0.5
0.0
-0.5
0
2
4
6
8
Time (µs)



Neutron
n
p
t

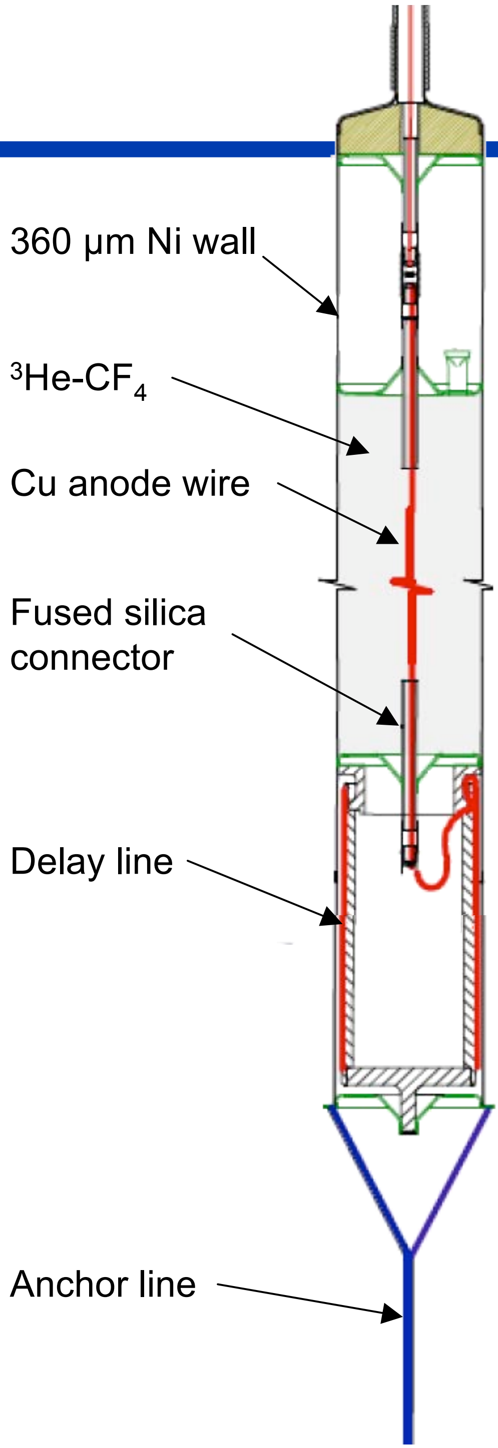


Current
20
15
10
5
0
0
1
2
3
4
5
Time (µs)

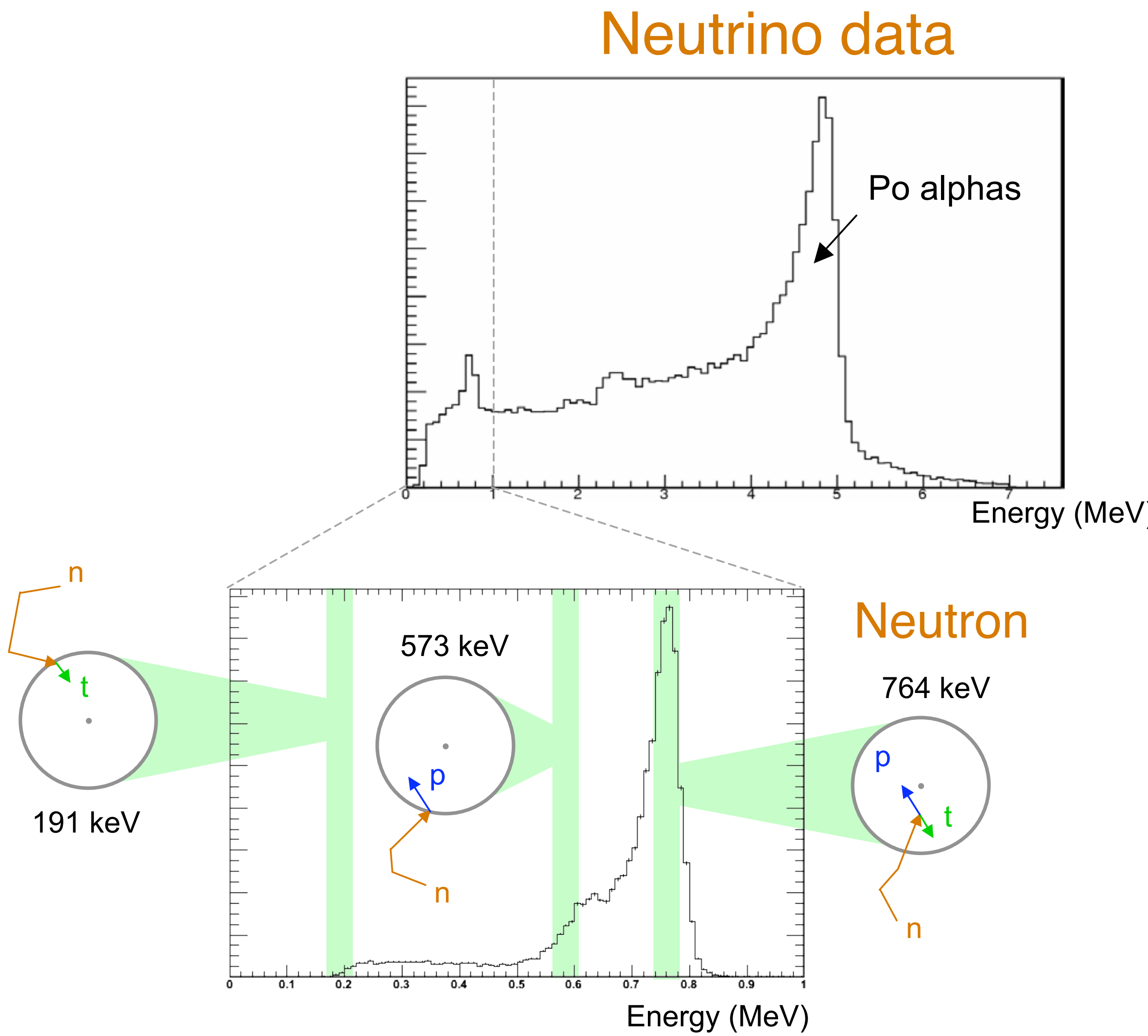


Alpha
α

Shaper-ADC



360 µm Ni wall
³He-CF₄
Cu anode wire
Fused silica connector
Delay line
Anchor line



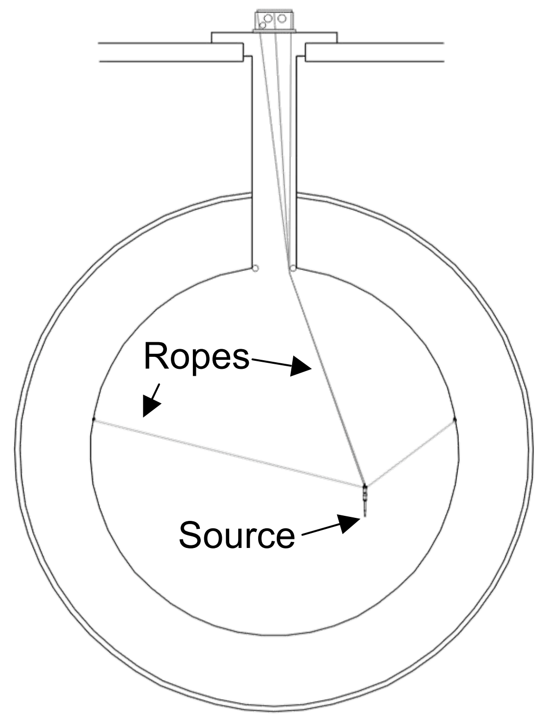
Neutrino data
Po alphas
Energy (MeV)
Neutron
n
t
191 keV
573 keV
p
764 keV
Energy (MeV)

Calibrations

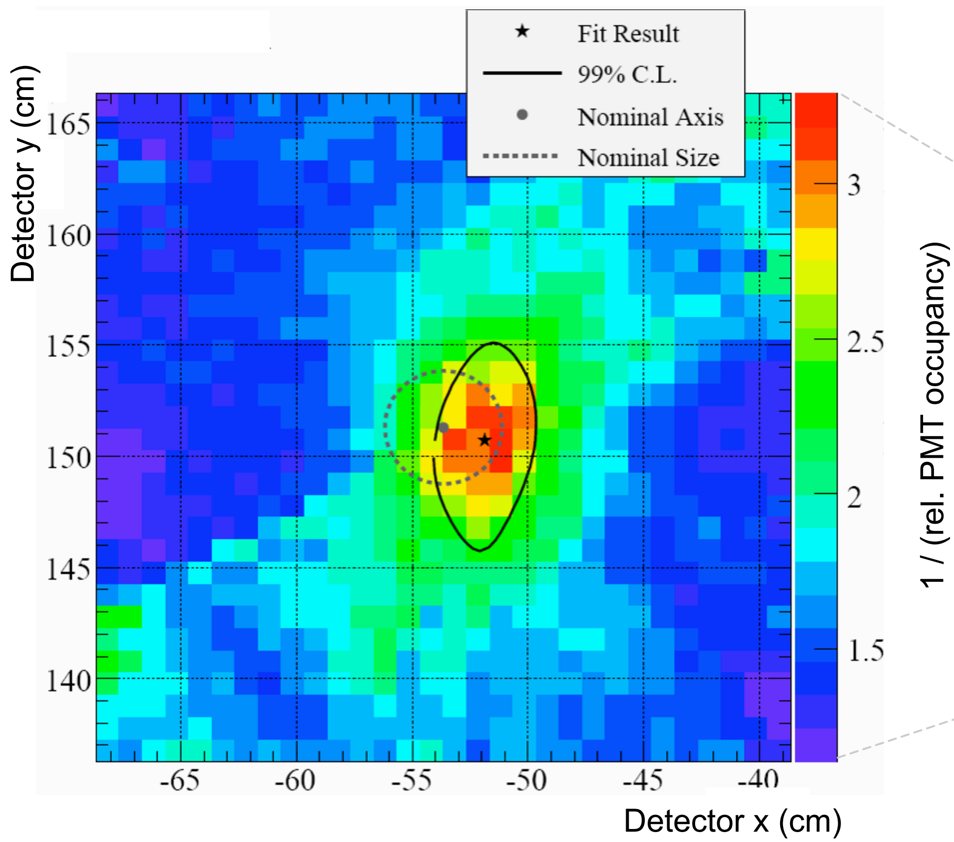
Source		PMT	NCD
Laserball	337-619 nm	Optics	
^{16}N	6.13 MeV γ	Energy	
^{8}Li	e^- spectrum		
AmBe	n		Neutron eff.
^{252}Cf	n		
^{24}Na ●	n		
Th	low E γ	Bkgrd. PDFs	
Rn ●	low E γ		

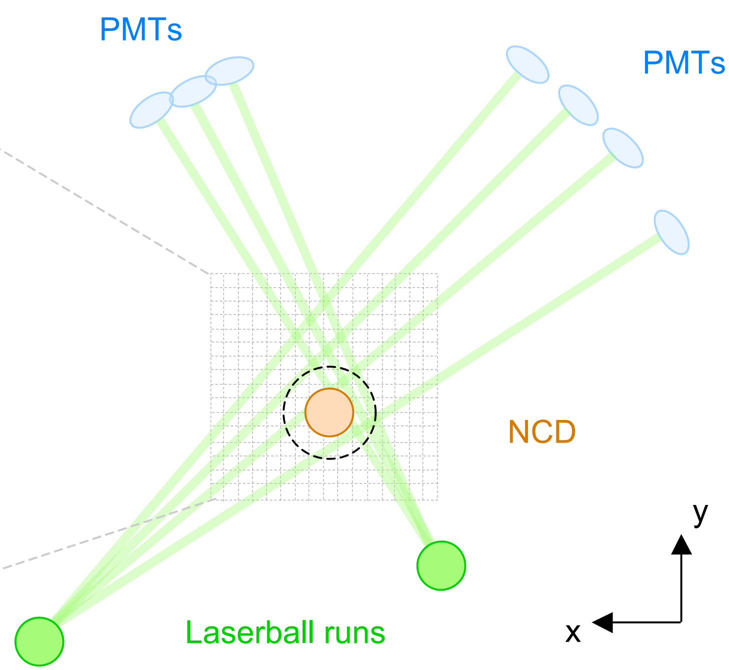
● Distributed source

Source-manipulator system capable of 2-5 cm positional accuracy



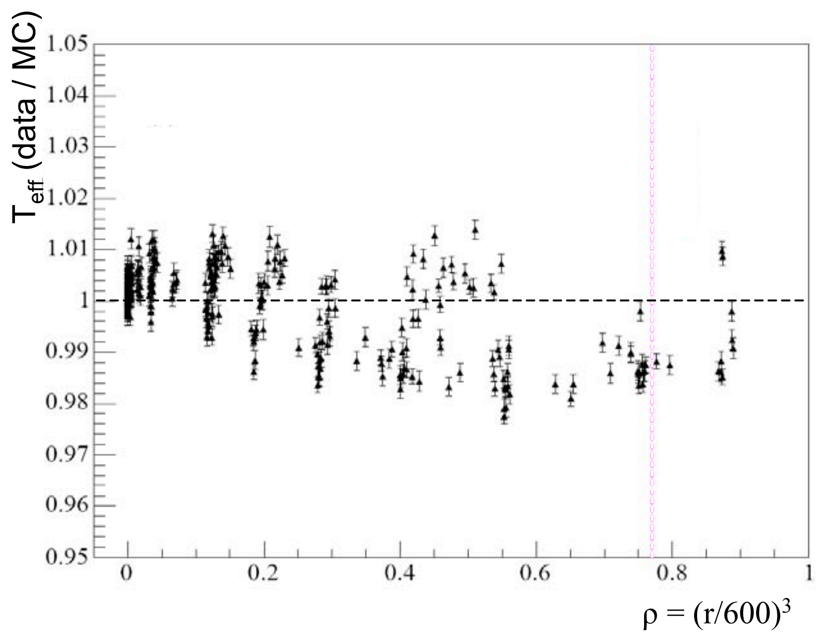
Optical Calibration



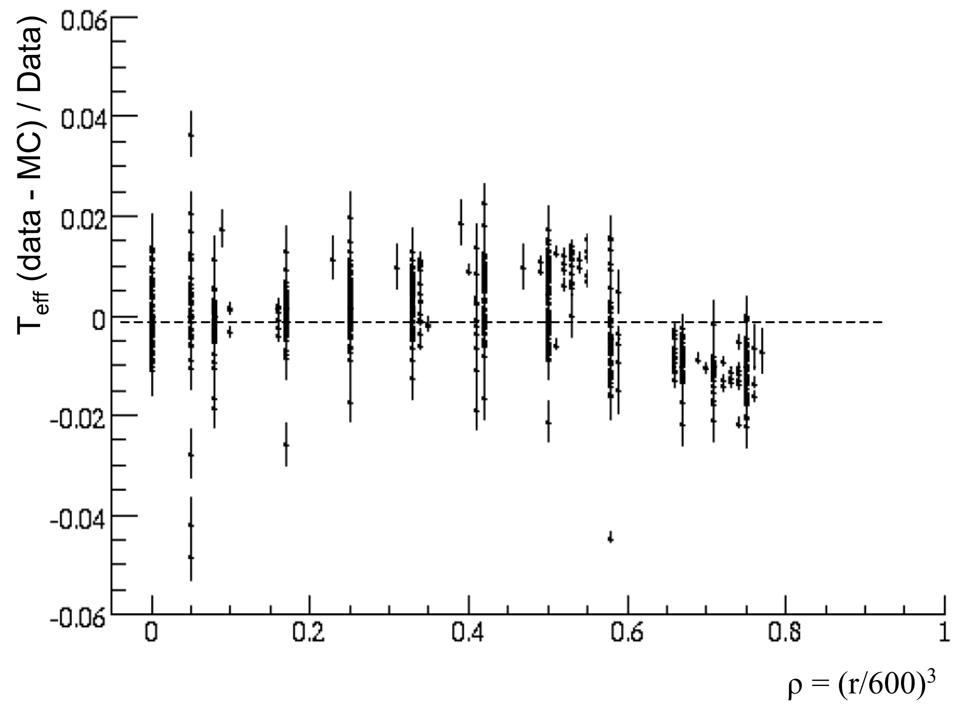


Energy Calibration - PMT

Salt phase



NCD phase



- $\Delta E/E$ = 1.1%
- Position and energy resolutions are comparable to the salt phase

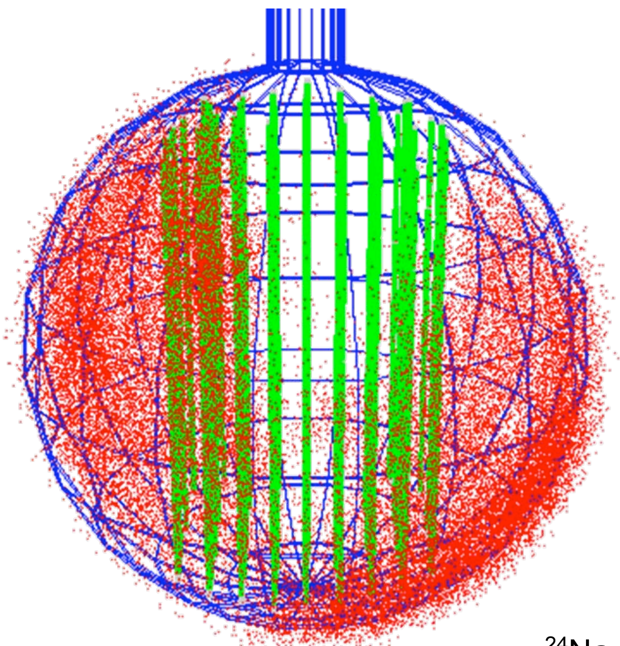
Neutron Calibration

^{24}Na method

Mimic the signal with mixed ^{24}Na, which generates neutrons by

$\gamma + {}^{2}H \rightarrow n + p$

$\varepsilon_n = 0.211 \pm 0.007$

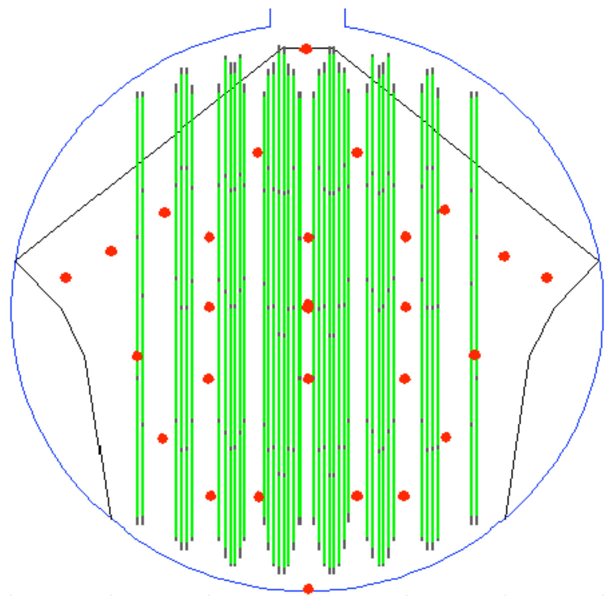


^{24}Na mixing in the heavy water

Monte Carlo method

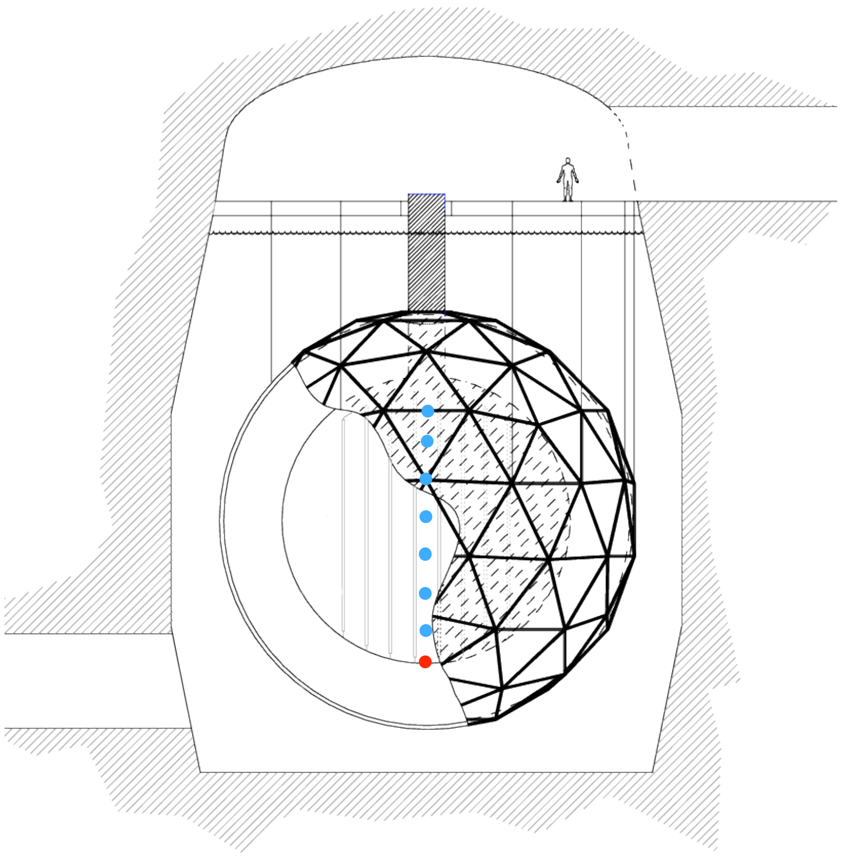
Calibrate the Monte Carlo with point AmBe and ^{252}Cf sources

$\varepsilon_n = 0.210 \pm 0.003$

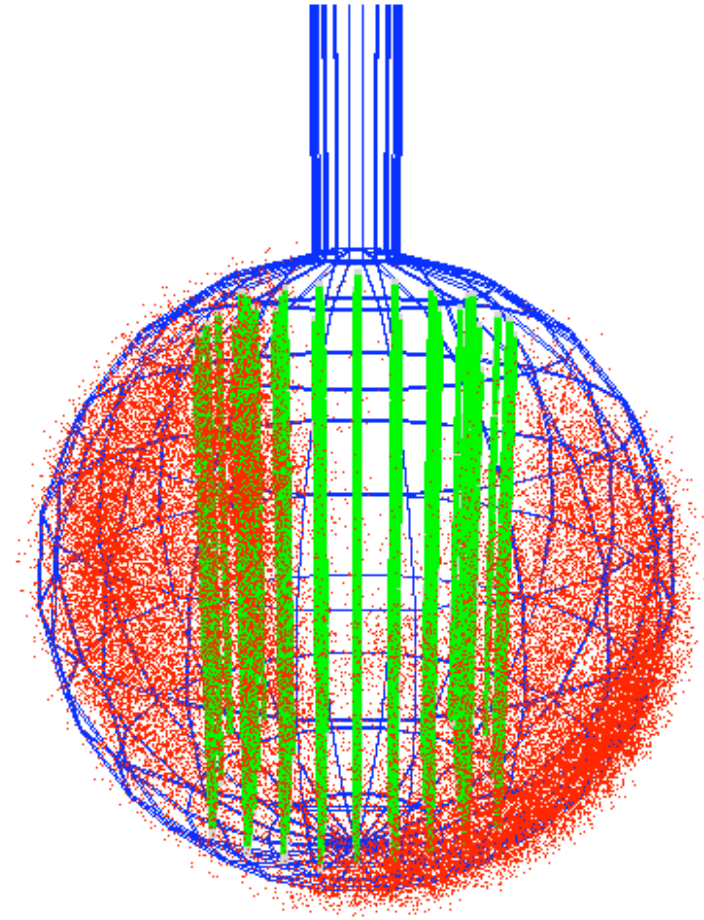


Typical source run locations (•)

^{24}Na Mixing



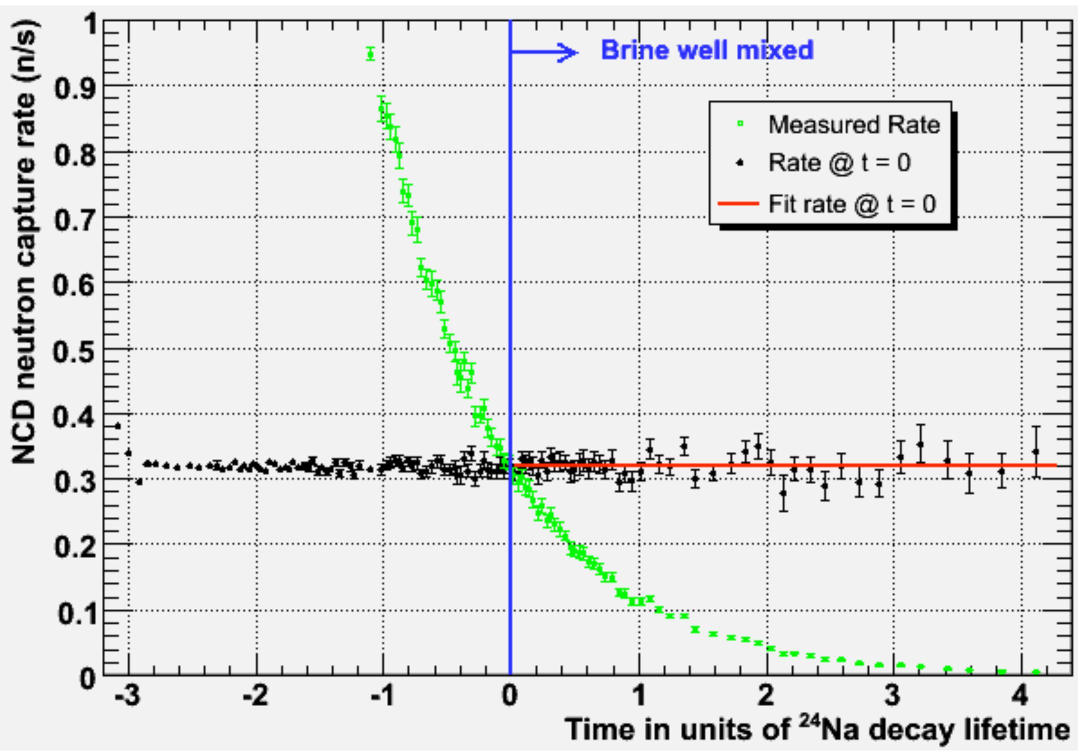
- 2005 injection points
- 2006 injection point



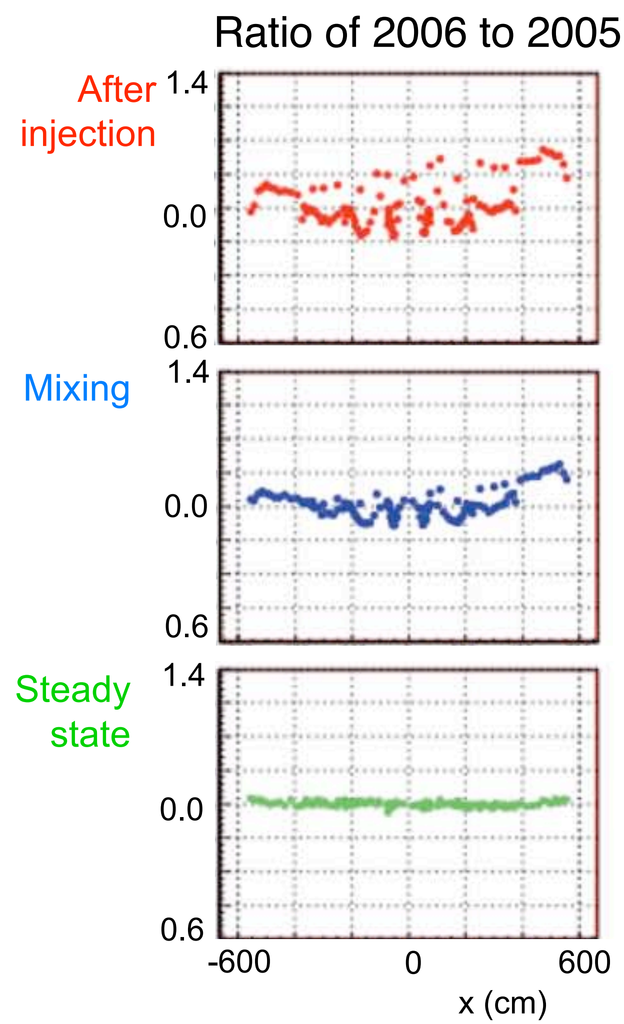
^{24}Na mixing during the 2006 spike

^{24}Na Mixing

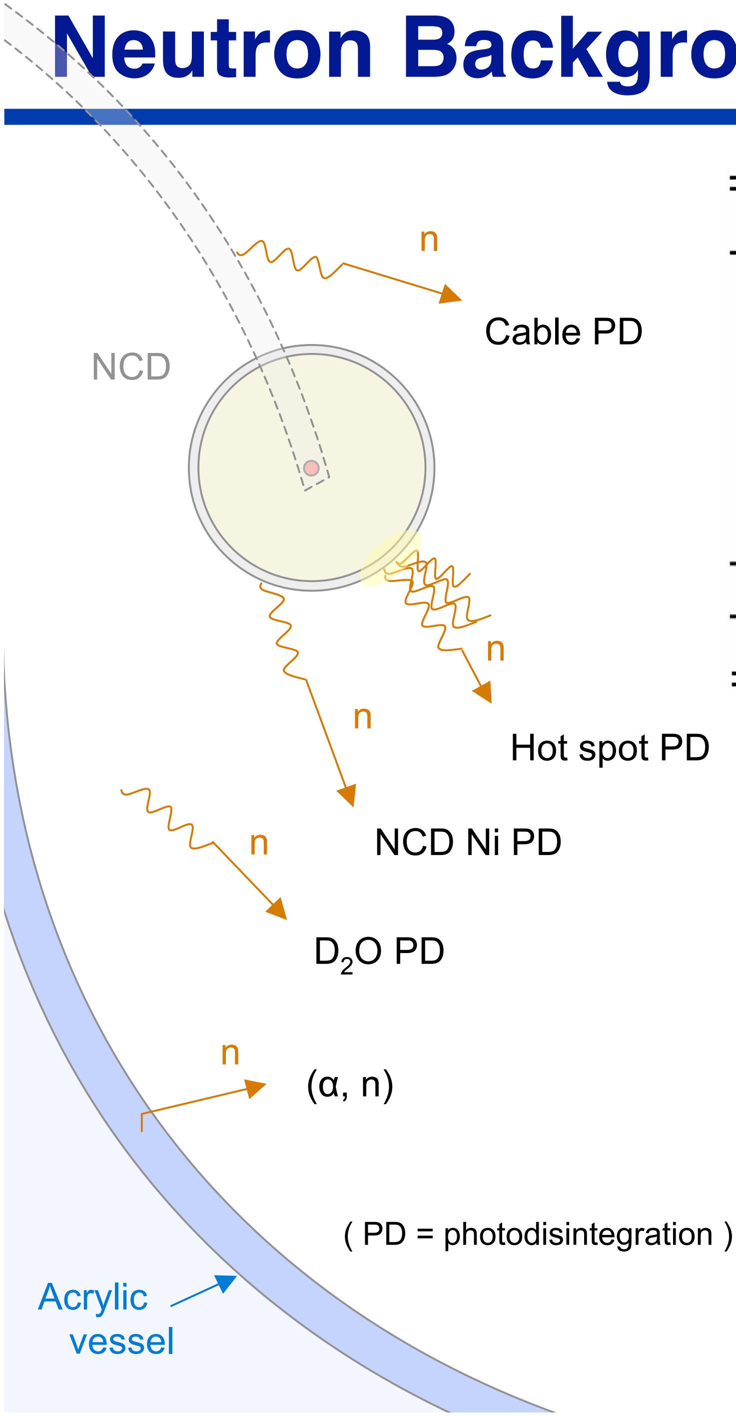
Neutrons



Gammas

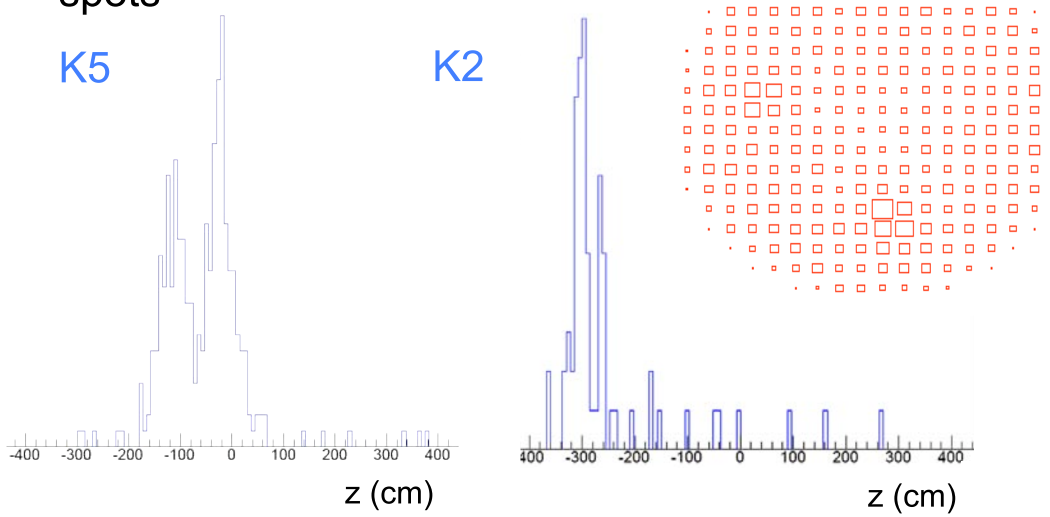


Neutron Backgrounds

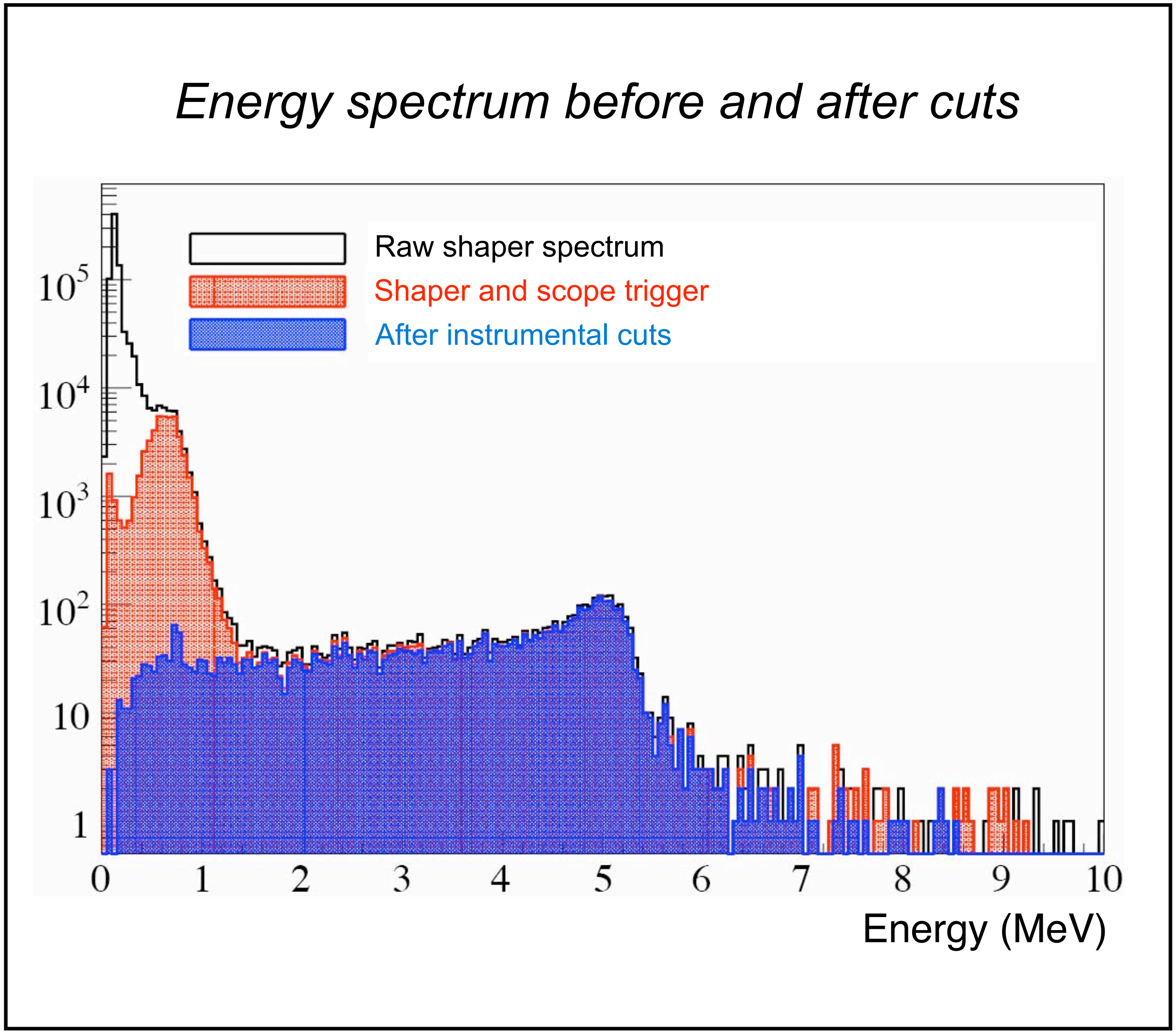


Source	PMT Events	NCD Events
D_2O photodisintegration	7.6 ± 1.2	28.7 ± 4.7
NCD bulk/^{17}O,^{18}O	$4.6^{+2.1}_{-1.6}$	$27.6^{+12.9}_{-10.3}$
Atmospheric ν/^{16}N	24.7 ± 4.6	13.6 ± 2.7
Other backgrounds †	0.7 ± 0.1	2.3 ± 0.3
NCD "hotspots"	17.7 ± 1.8	64.4 ± 6.4
NCD cables	1.1 ± 1.0	8.0 ± 5.2
Total internal neutron background	$56.4^{+5.6}_{-5.4}$	$144.6^{+13.8}_{-14.8}$
External-source neutrons	20.6 ± 10.4	40.9 ± 20.6

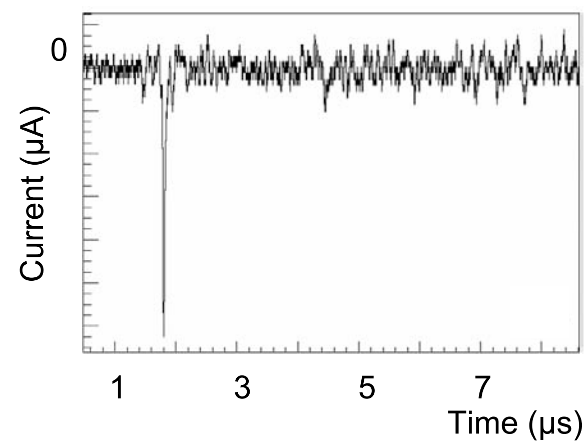
Hot spots

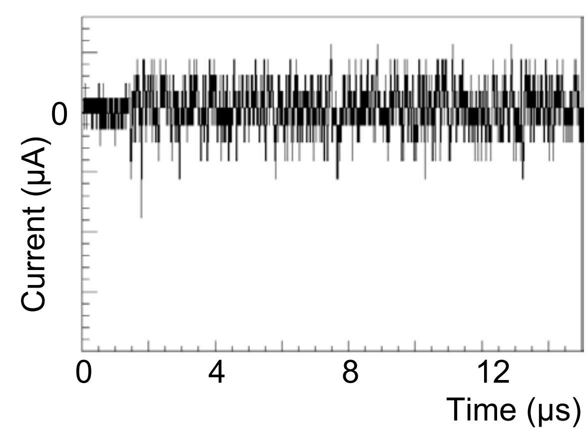


Instrumental Background Cuts



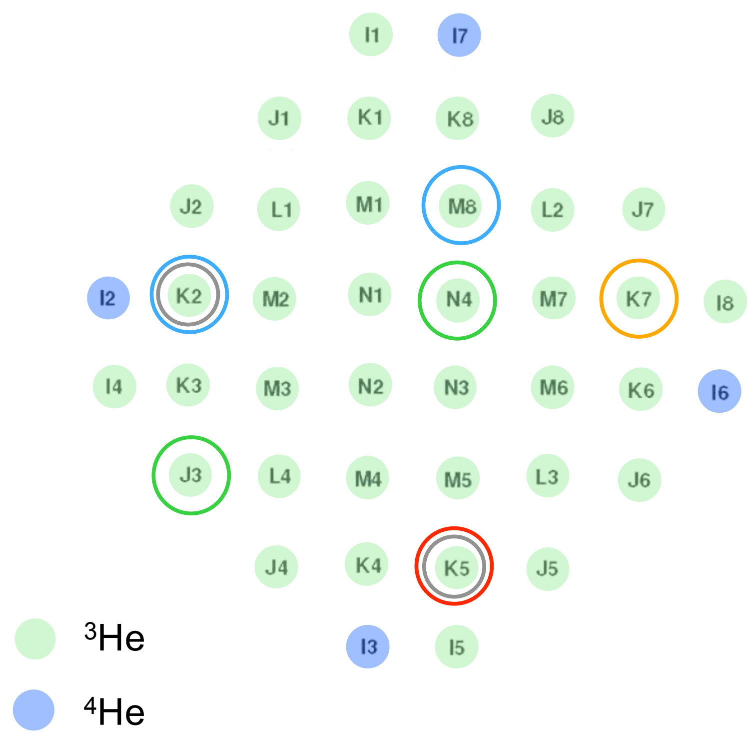
- Time domain cuts
- Frequency domain cuts
- Burst cuts

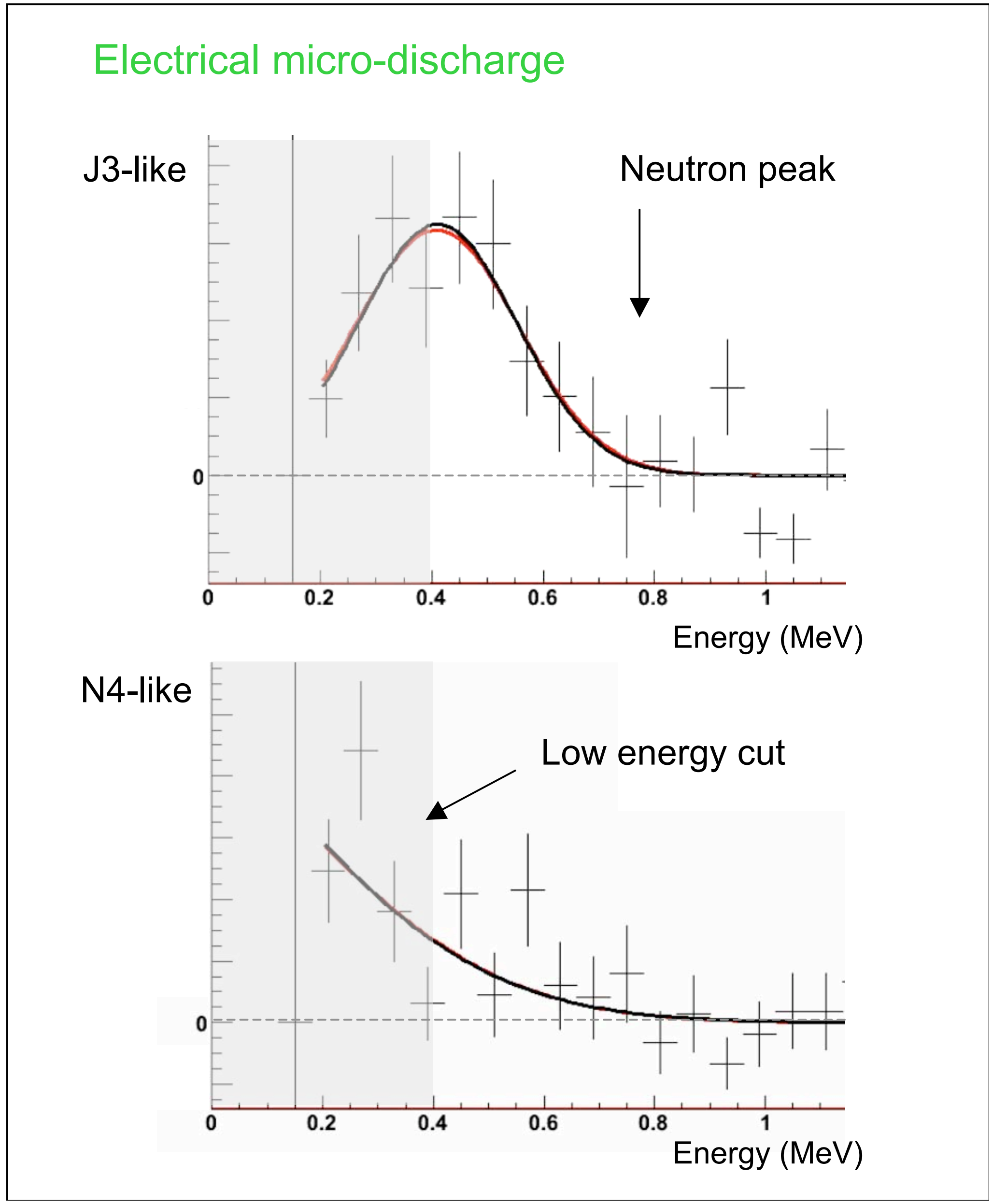




Instrumental Backgrounds

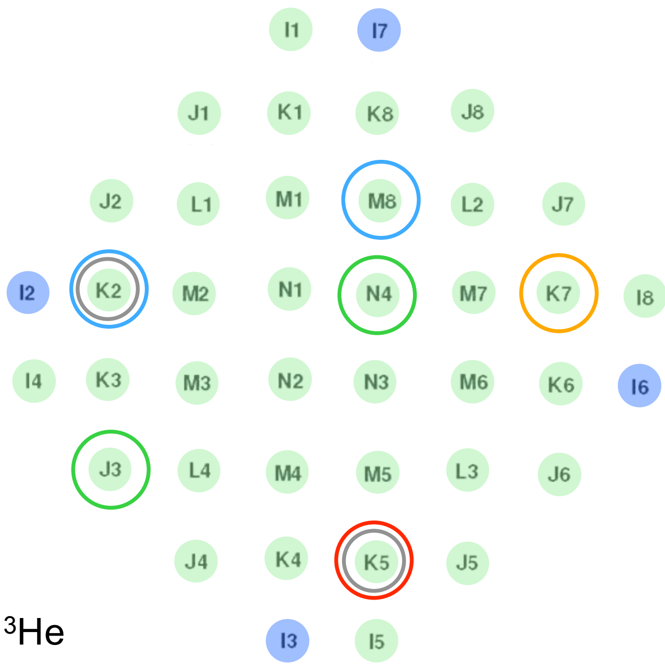
- Hot spot
- Gas leak into counter inter-space
- Electrical disconnect
- Electrical micro-discharge
- Gain instability





Problems with Other Strings

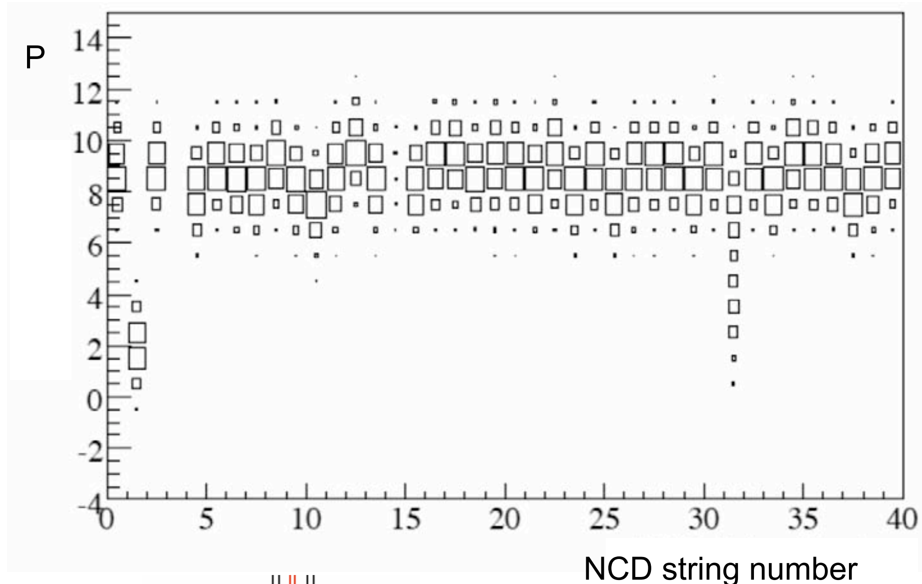
- Hot spot
- Gas leak into counter inter-space
- Electrical disconnect
- Electrical micro-discharge
- Gain instabilities

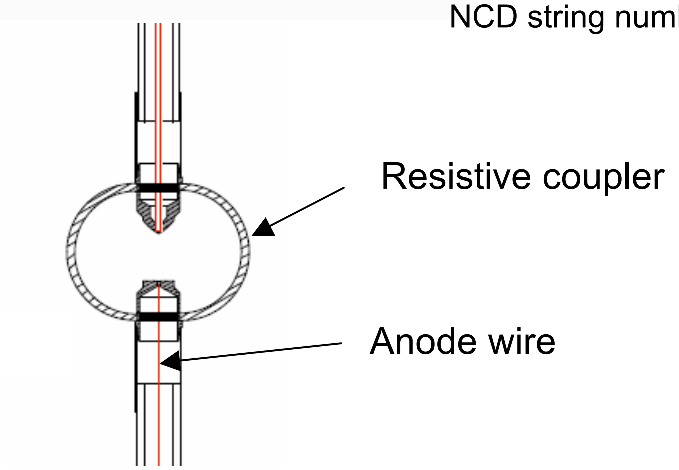


^3He

^4He

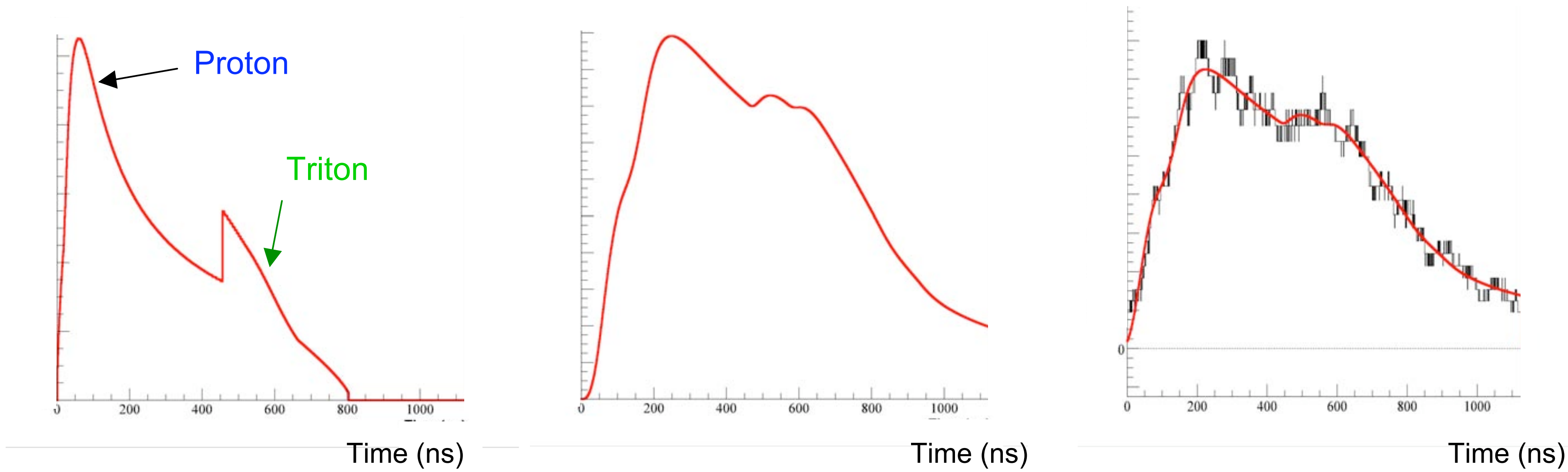
Electrical disconnect





Simulating an NCD Pulse

Energy deposition, electron drift — Charge multiplication, ion drift, pulse propagation, electronics — Noise



Pulse simulation : α energy loss, α straggling, α multiple scattering

electron-ion pair generation

electron drift, diffusion

electron multiple scattering

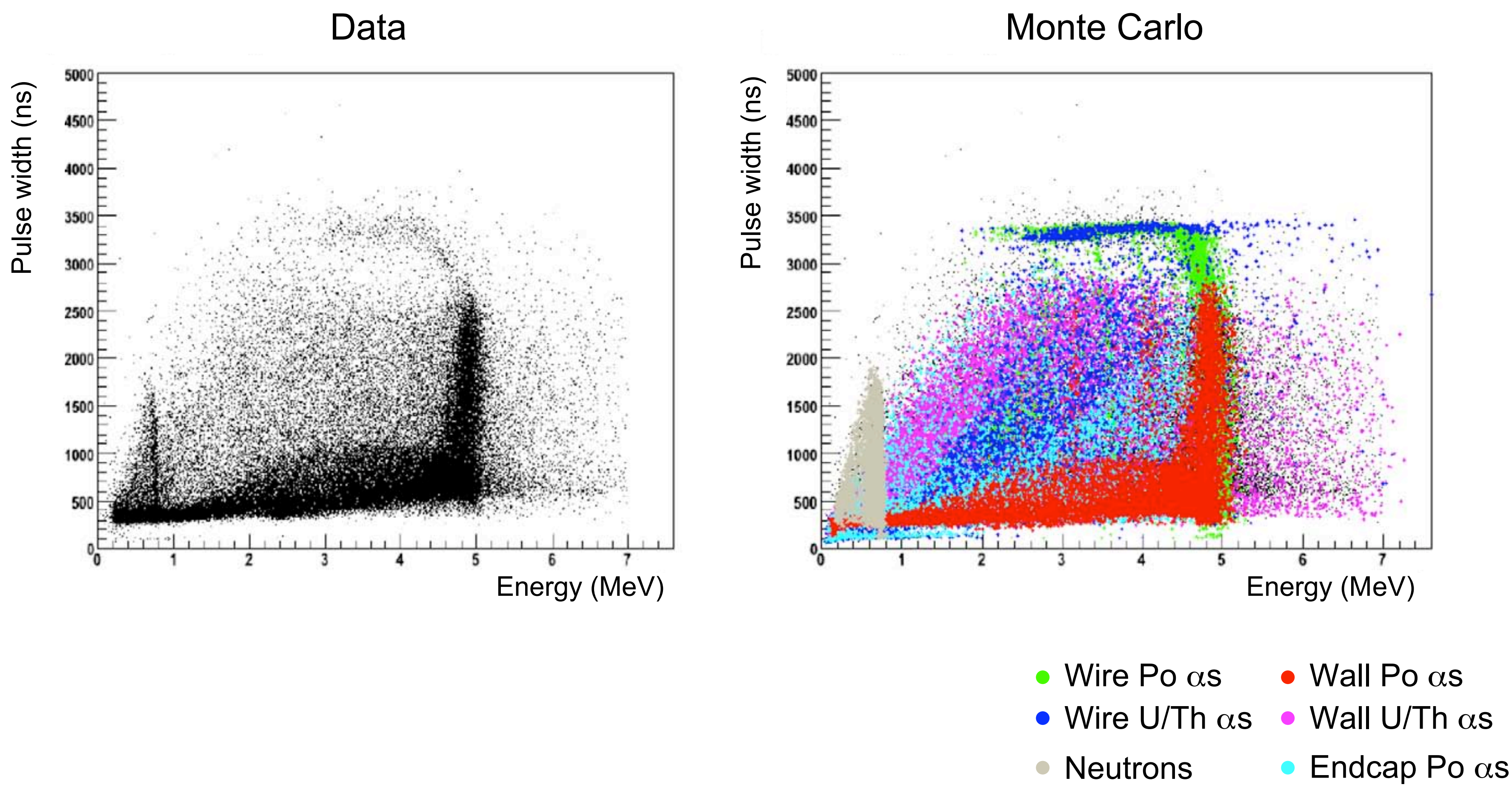
ion mobility

electron avalanche

space charge

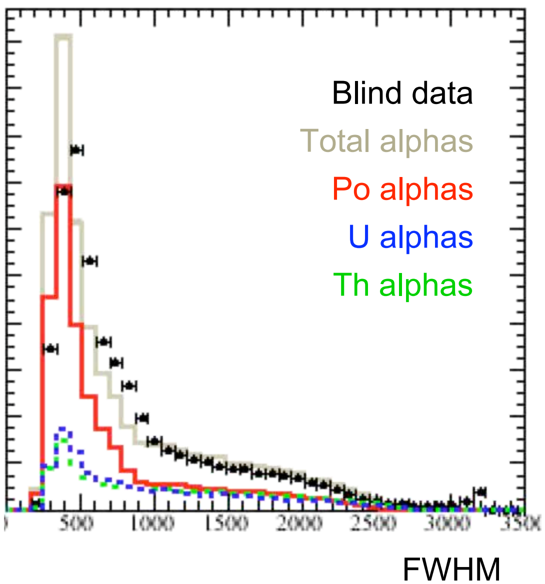
signal generation, electronics, noise

Comparisons with Data

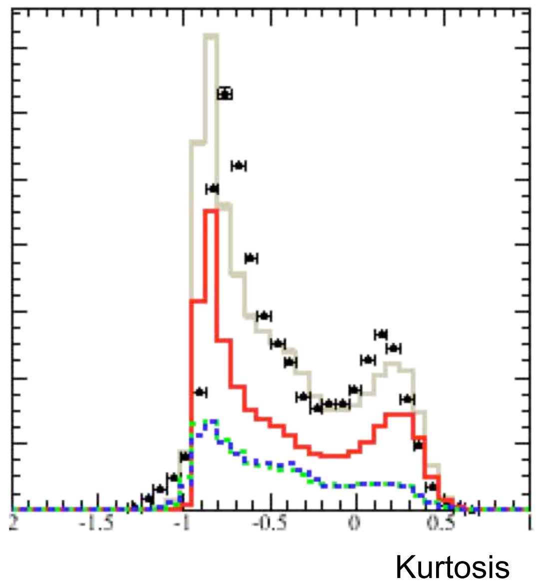


Alpha Pulse Simulation

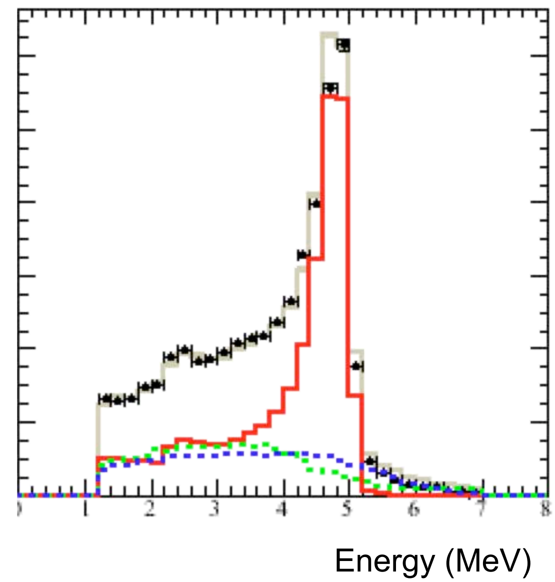
Width



Kurtosis

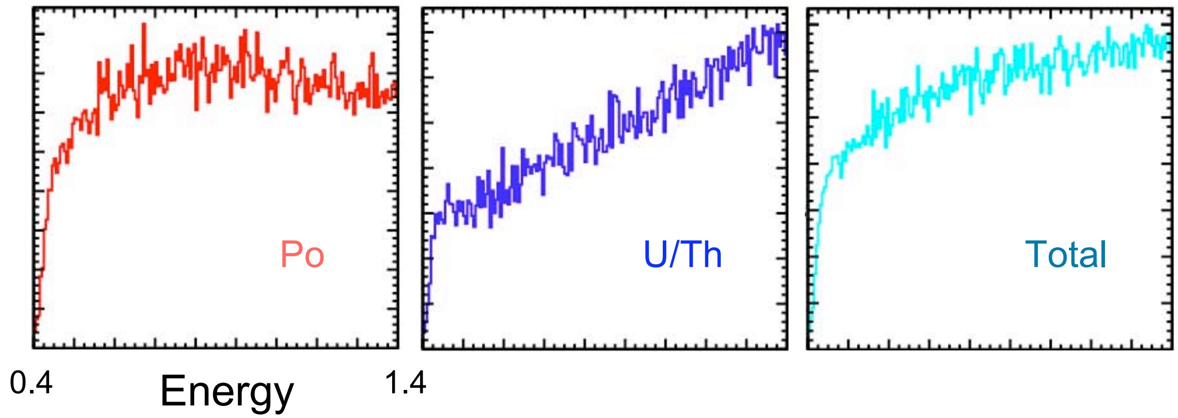


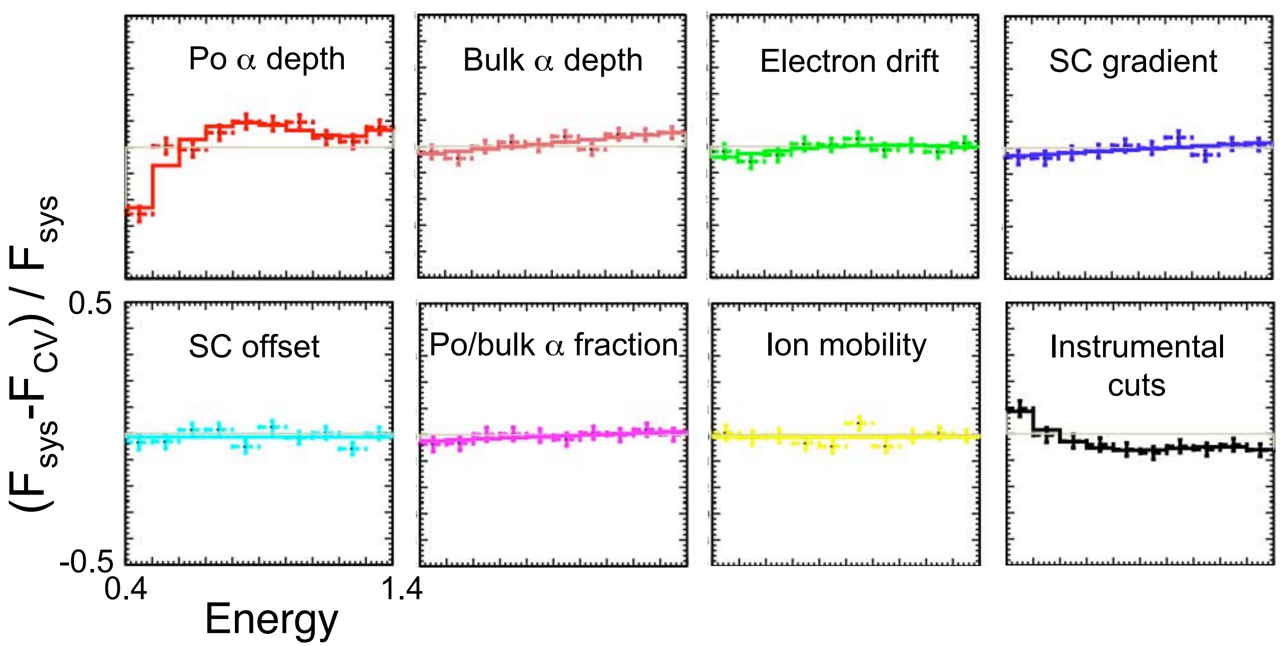
Energy



- Relative contributions of U, Th and Po alphas fit using data above the neutron (signal) energy window.

Alpha Energy Spectrum





Relative contributions of these different systematics are constrained by the neutrino data

Blind Analysis

- First month of neutrino data open

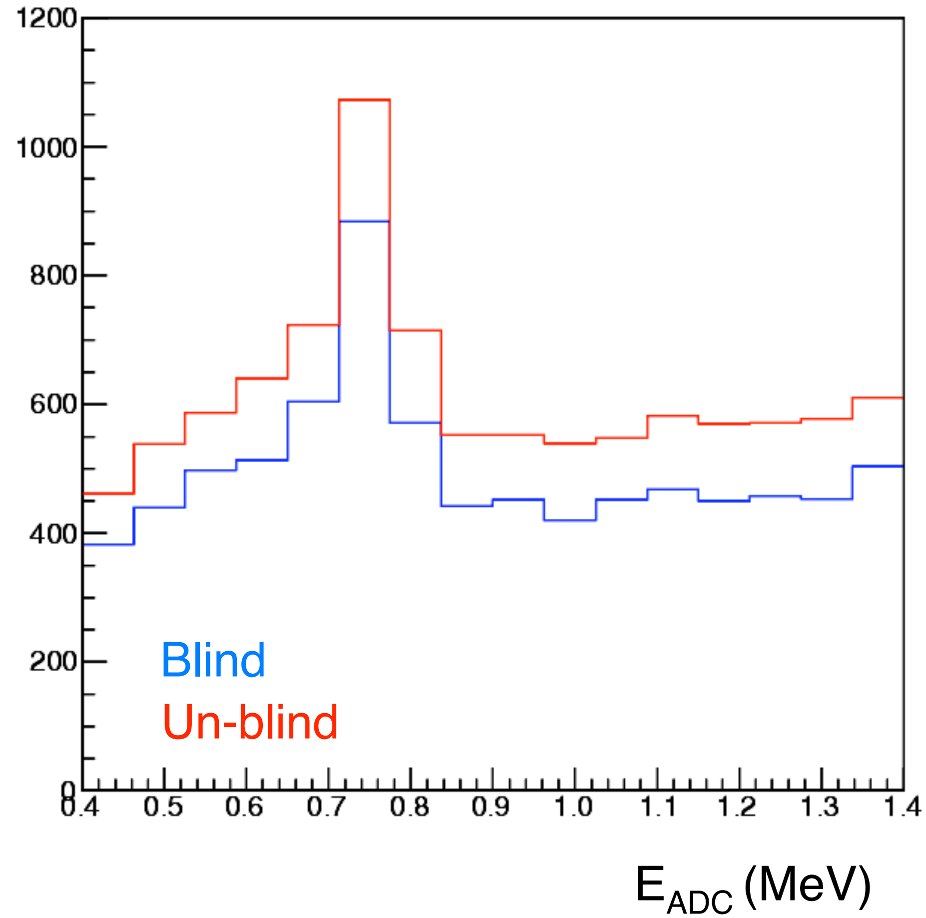
- Then only 20% open to Dec. 2005 to finalize instrumental background cuts (*instrumental cut bias*)

- Thereafter include hidden fraction of neutrons that follow muons (*change S/B ratio*)

AND

- Omit an unknown fraction of candidate events (*change S/B ratio*)

Detailed internal documentation, review by "topic committees"



Box Opened May 2, 2008

Neutrino Signal Extraction

Live time	385.17 days		
NCD raw triggers	1,417,811	PMT raw triggers	146,431,346
NCD υ candidates	7,302	PMT υ candidates	2,381

- PDFs and observables
- Systematic uncertainties
- Backgrounds

$$L = L_{PMT} + L_{NCD}$$

$$L_{PMT} = -\sum_{d=1}^{N_d} \log\left(\sum_{s=1}^{N_s} n_s f_s(\bar{x_d})\right) + \sum_{s=1}^{N_s} n_s - \frac{1}{2}\sum_{p=1}^{N_p}\left(\frac{\lambda_p - \bar{\lambda_p}}{\bar{\sigma_p}}\right)^2$$

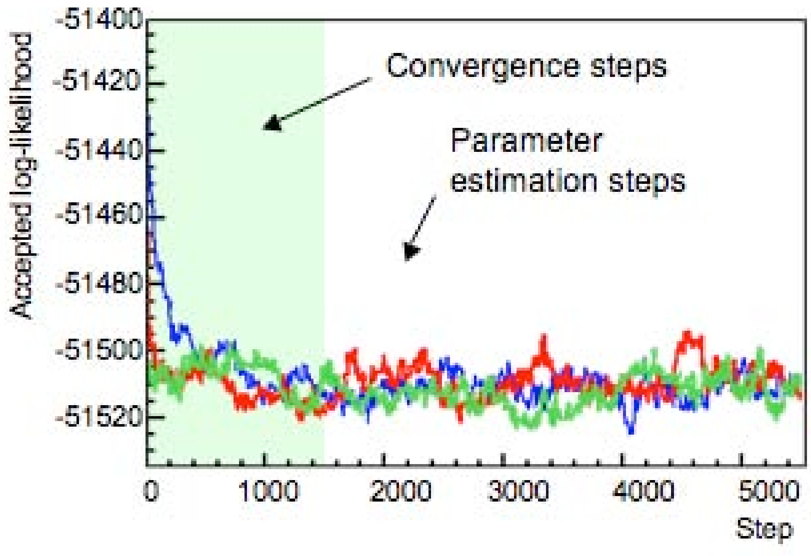
$$L_{NCD} = -\sum_{d=1}^{N'_d} \log\left(\sum_{s=1}^{N'_s} n'_s f'_s(\bar{x_d})\right) + \sum_{s=1}^{N'_s} n'_s - \frac{1}{2}\sum_{p=1}^{N'_p}\left(\frac{\lambda'_p - \bar{\lambda'_p}}{\bar{\sigma'_p}}\right)^2$$

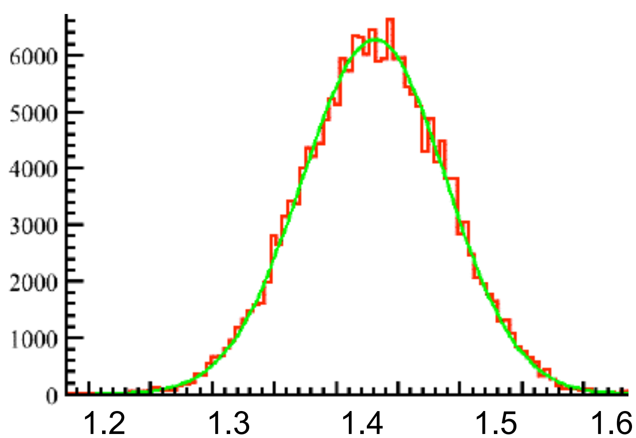
62-parameter likelihood function

- 13 CC flux energy bins
- 13 ES flux energy bins
- NC flux
- 35 systematic parameters

3 independent algorithms to determine the neutrino fluxes

Markov Chain Monte Carlo (MCMC)





A posterior distribution

Try to sample parameter space (instead of a 62-parameter MINUIT fit)

Initial step i

- parameter guesses p_i
- calculate likelihood L_i

Add random amounts to all p_i:

- $p_{i+1} = p_i + \mathrm{Norm}(0,\sigma_i)$
- calculate likelihood L_{i+1}

if (Uniform(0,1) > $\min(1, L_i/L_{i+1})$):

- keep p_{i+1}

else: keep p_i ; start again

Metropolis-Hastings method

After "burn-in" the start point is forgotten and the algorithm samples the function correctly.

Systematics Table

Nuisance Parameter	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
PMT energy scale	±0.6	±2.7	±3.6
PMT energy resolution	±0.1	±0.1	±0.3
PMT radial scaling	±0.1	±2.7	±2.7
PMT angular resolution	±0.0	±0.2	±2.2
PMT radial energy dep.	±0.0	±0.9	±0.9
Background neutrons	±2.3	±0.6	±0.7
Neutron capture	±3.3	±0.4	±0.5
Cherenkov/AV backgrounds	±0.0	±0.3	±0.3
NCD instrumentals	±1.6	±0.2	±0.2
NCD energy scale	±0.5	±0.1	±0.1
NCD energy resolution	±2.7	±0.3	±0.3
NCD alpha systematics	±2.7	±0.3	±0.4
PMT data cleaning	±0.0	±0.3	±0.3
Total experimental uncertainty	±6.5	±4.0	±4.9
Cross section [16]	–	±1.2	±0.5

NC

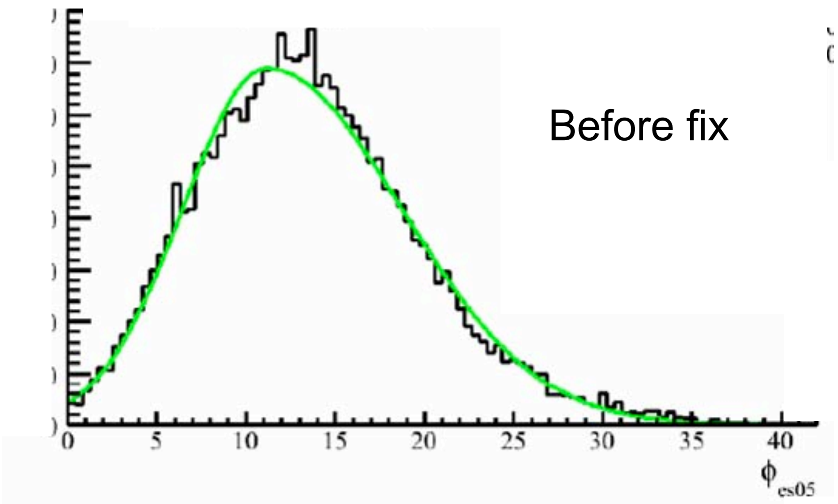
Detection efficiency	3.3%
NCD energy resolution	2.7%
NCD alpha background	2.7%
Neutron background	2.3%

CC

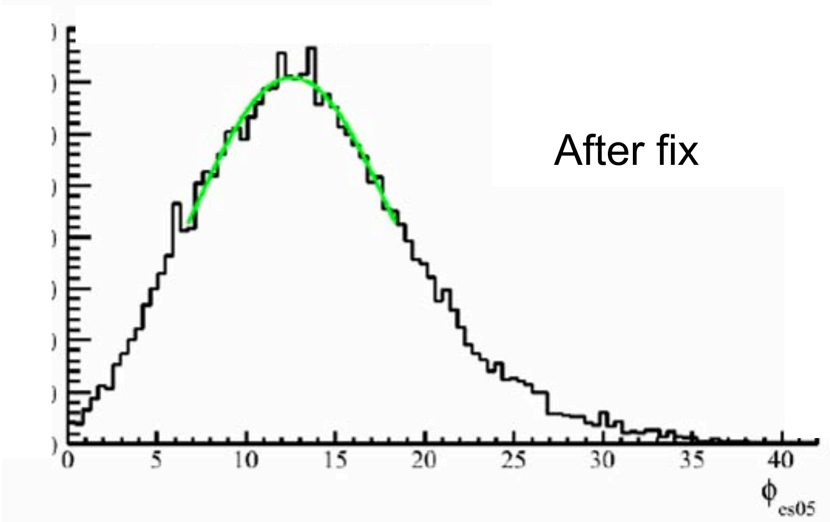
PMT energy scale	2.7%
PMT radial scale	2.7%

Opening the Box

ES 5th energy bin posterior



Before fix



After fix

Three algorithms :

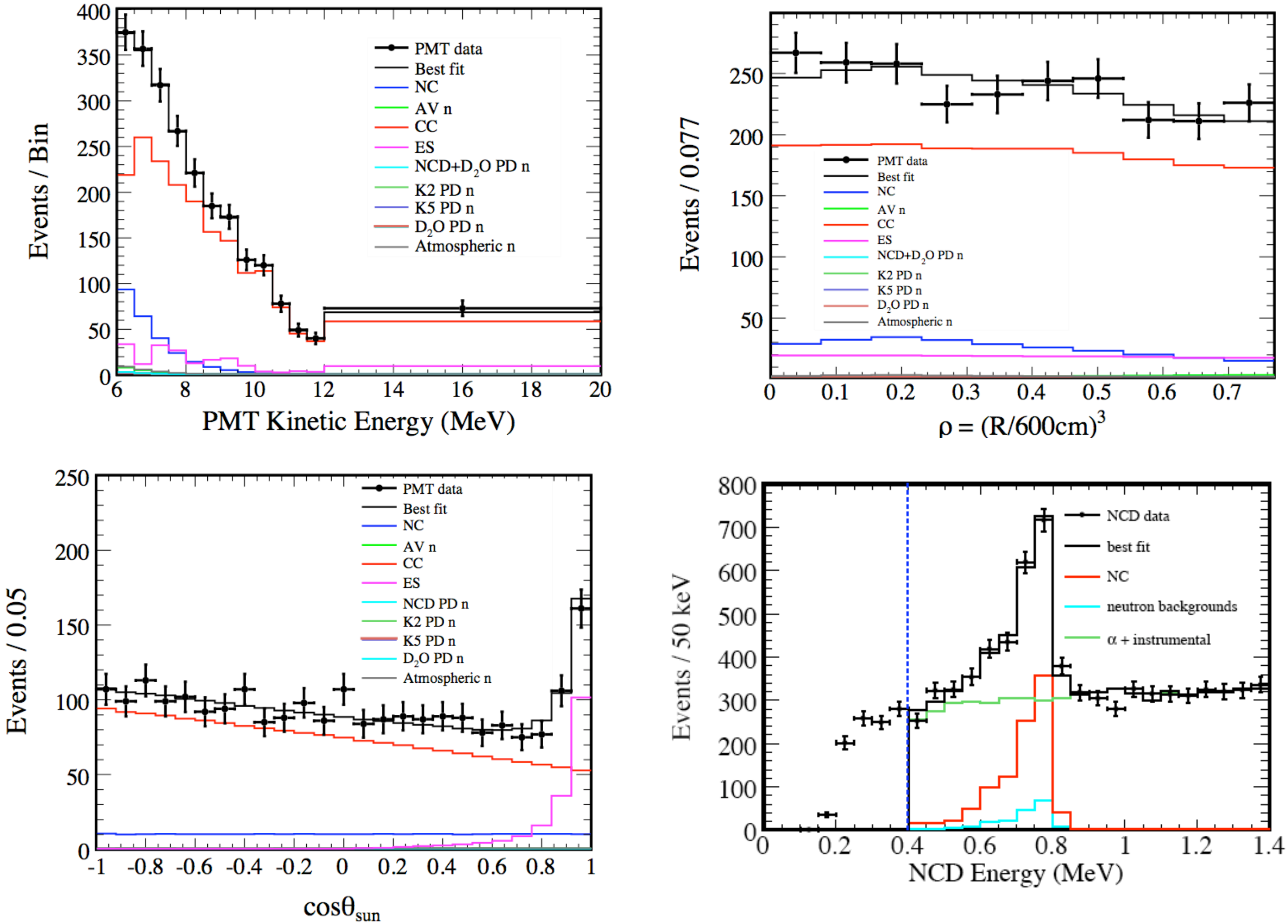
- Markov Chain Monte Carlo (MCMC)
- Maximum Likelihood with randomly sampled systematics
- Maximum Likelihood with floating and shift-re-fit systematics

Post box opening :

(1) 10% difference in NC flux uncertainty between analyses

(2) MCMC ES flux low by 0.5 σ

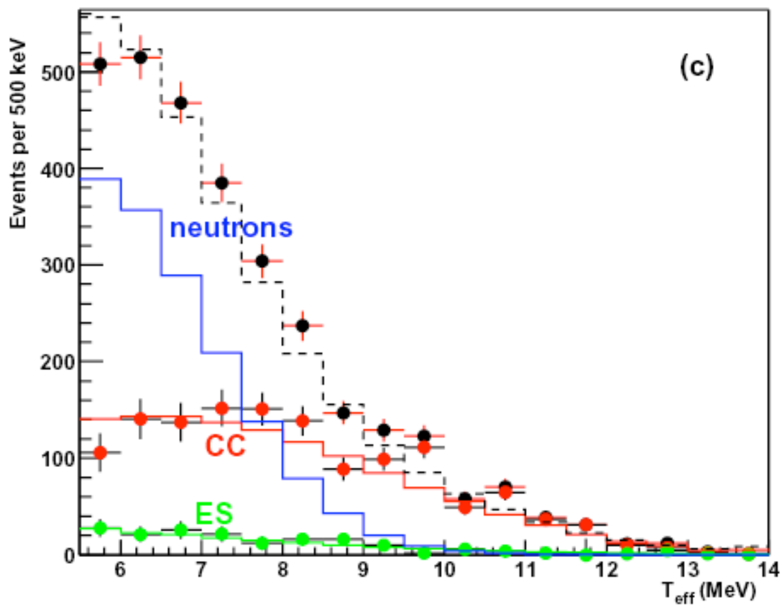
Results



Events / Bin
PMT Kinetic Energy (MeV)
PMT data
Best fit
NC
AV n
CC
ES
NCD+D$_2$O PD n
K2 PD n
K5 PD n
D$_2$O PD n
Atmospheric n
Events / 0.077
ρ = (R/600cm)^3
Events / 0.05
cosθ$_{sun}$
NCD PD n
Events / 50 keV
NCD Energy (MeV)
NCD data
best fit
neutron backgrounds
α + instrumental

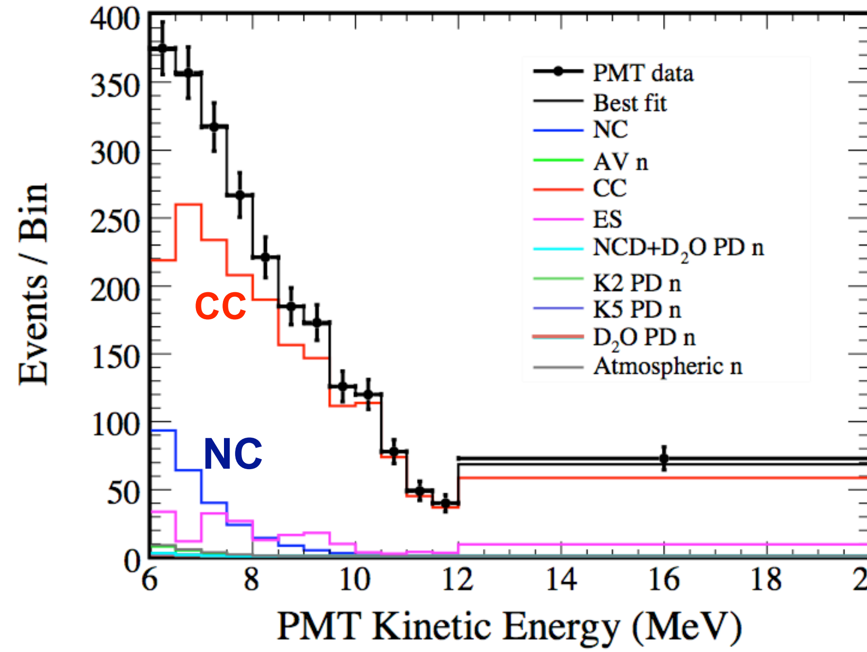
Compare to Salt Phase

Salt



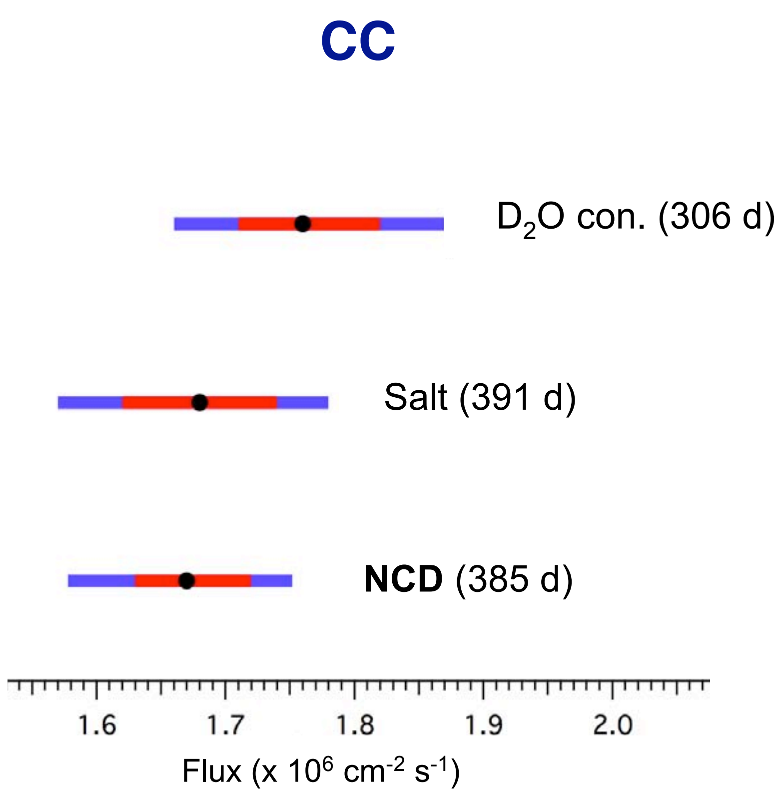
	CC	ES	NC
CC	1.00		
ES	-0.16	1.00	
NC	-0.52	-0.06	1.00

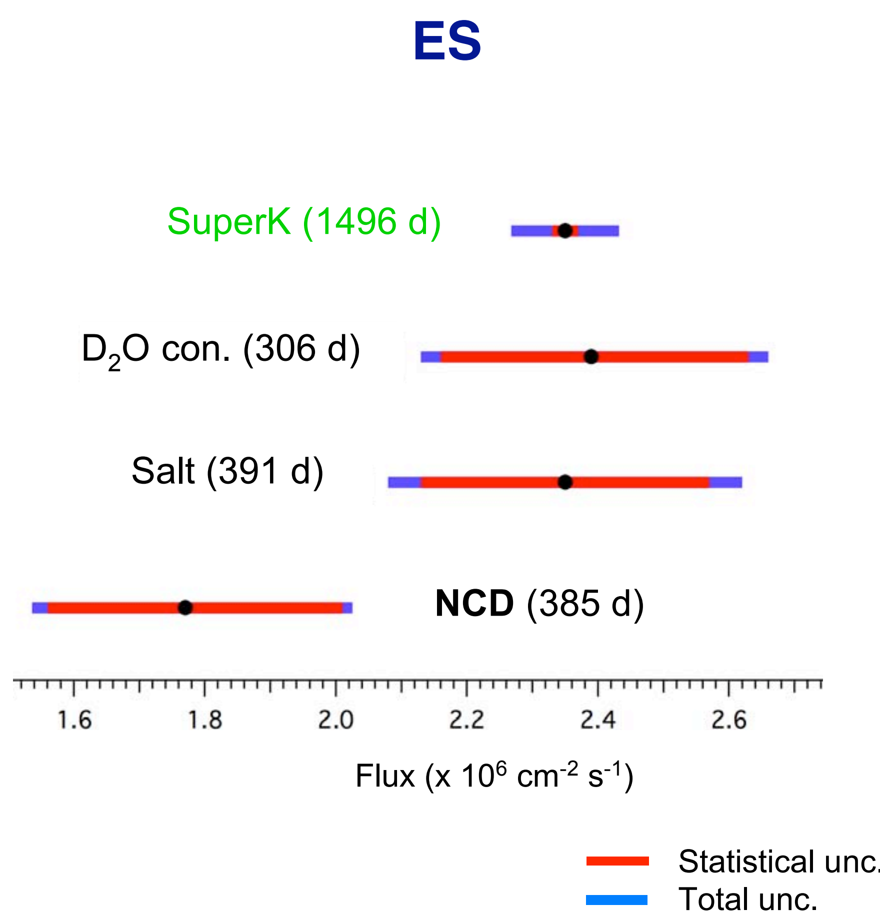
NCD



	CC	ES	NC
CC	1.00		
ES	0.24	1.00	
NC	-0.19	0.02	1.00

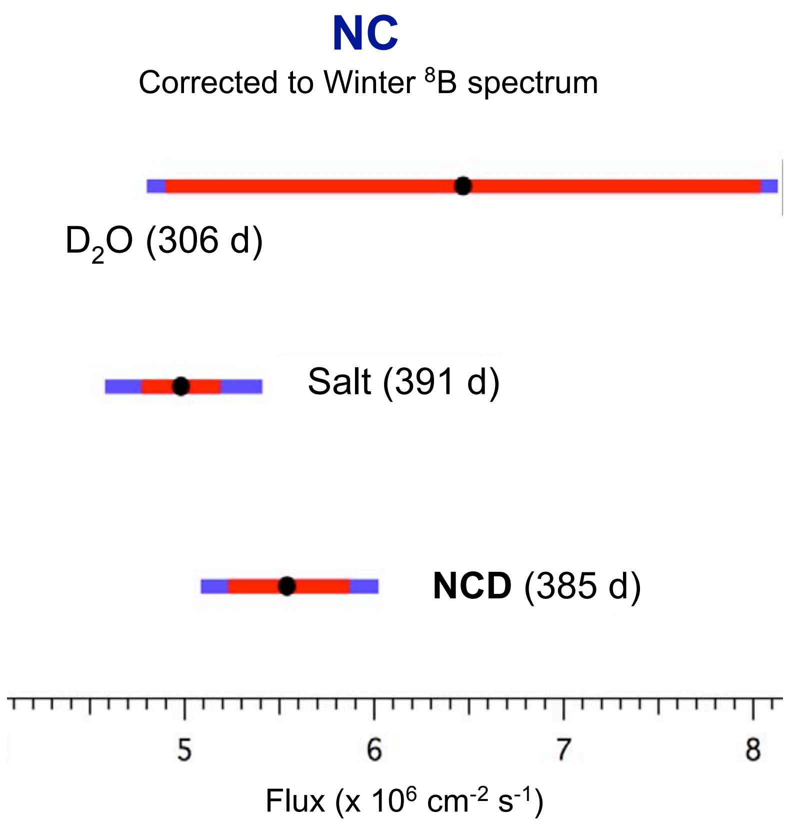
Comparisons



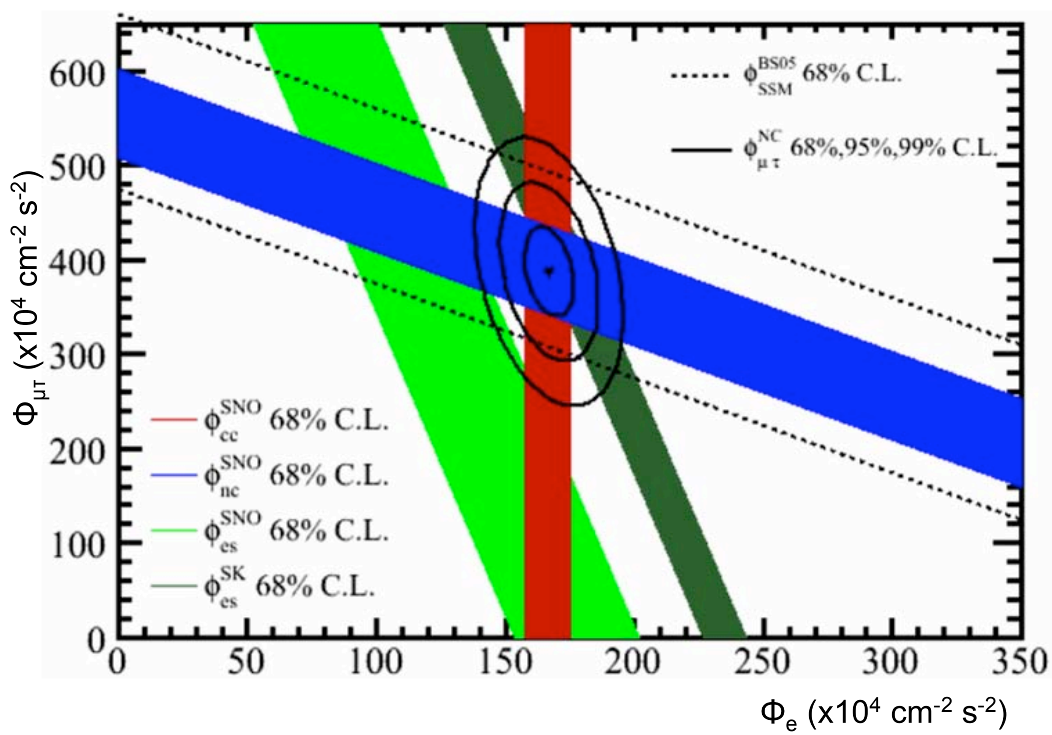


CC	$1.67^{+0.05}_{-0.04}$ (stat) $^{+0.07}_{-0.08}$ (sys) × 10^6 υ $cm^{-2}s^{-1}$
ES	$1.77^{+0.24}_{-0.21}$ (stat) $^{+0.09}_{-0.10}$ (sys)
NC	$5.54^{+0.33}_{-0.32}$ (stat) $^{+0.36}_{-0.24}$ (sys)

Comparisons



- Agreement with past measurements (estimated p-value = 0.328)
- Agreement with standard solar models



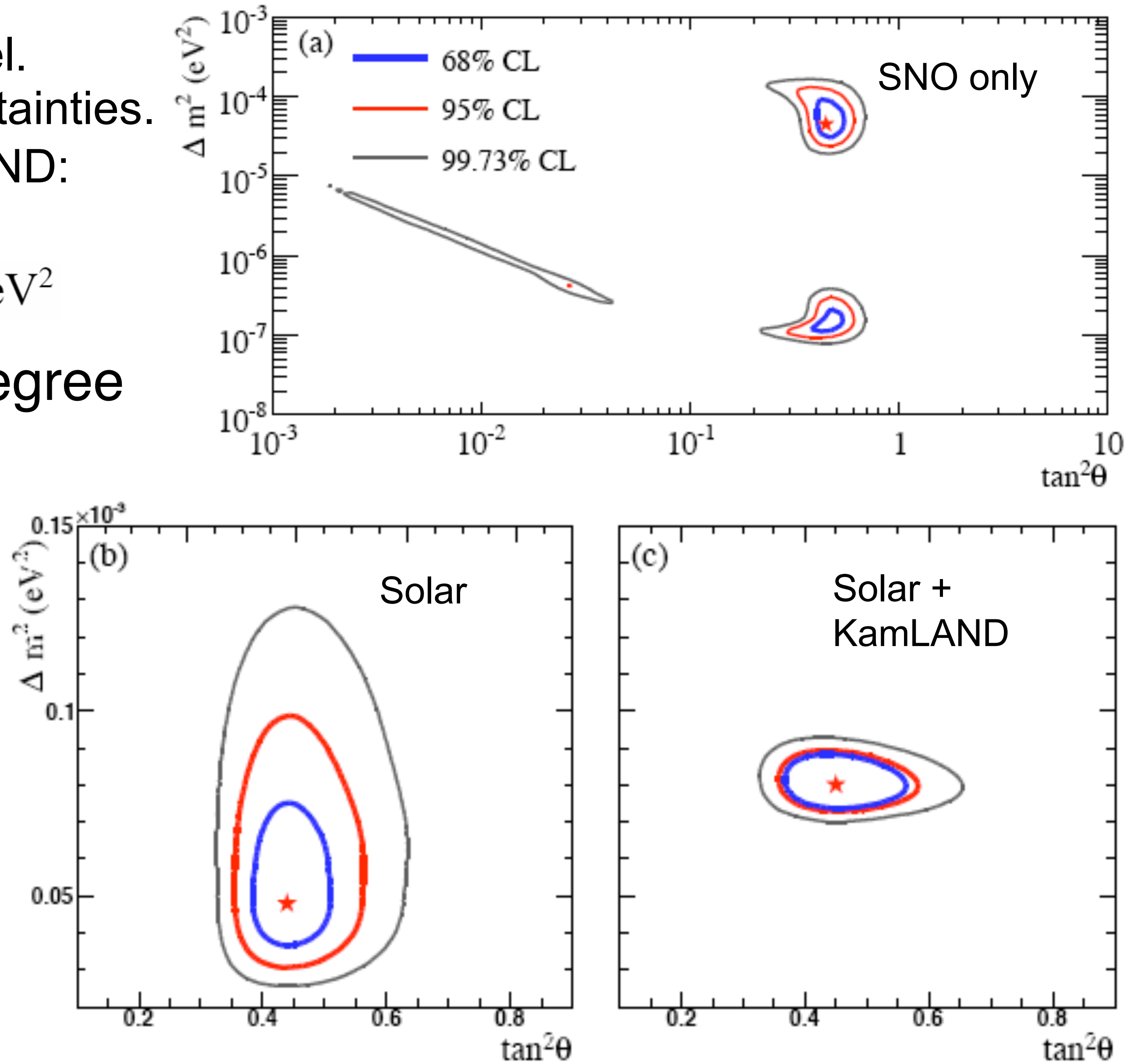
$\phi_{SSM} = 569(1 \pm 0.16) \times 10^4\ cm^{-2}\ s^{-1}$ (BSB05-OP: Bahcall, Serenelli, Basu Ap. J. 621, L85, 2005).

MSW Contours

- 2-neutrino mixing model.
- Marginalized 1-σ uncertainties.
- Solar + 766 t-y KamLAND:

$$\Delta m^2_{12} = 7.94^{+0.42}_{-0.26} \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{12} = 33.8^{+1.4}_{-1.3}$$ degree



Cl-Ar
Super-K
SAGE
Gallex
GNO
SNO
Borexino (first result)

766 t-y KamLAND

Summary

- A model independent measurement of the ^{8}B flux
- Improved precision on mixing angle θ
- Reduced correlation between CC and NC
- Different systematics
- Agreement with previous measurements

More from SNO

- LETA (Low E Threshold Analysis) of Phases I and II (T=3.5-4 MeV)
- Muons, atmospheric ν
- Three-phase solar neutrino analysis
- Three-neutrino mixing analysis
- Three-phase *hep* flux
- Three-phase solar neutrino Day-Night Asymmetry

arXiv:0806.0989v1 [nucl-ex]

Expect the Unexpected

- Found at the bottom of the cavity:

The SNO Collaboration

The SNO collaboration

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